

**PROPORTIONAL AND NON-PROPORTIONAL  
TRANSFER OF MOVEMENT SEQUENCES**

A Dissertation

by

HEATHER JO WILDE

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2004

Major Subject: Kinesiology

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December 2004

Major Subject: Kinesiology

## **ABSTRACT**

Proportional and Non-Proportional Transfer  
of Movement Sequences. (December 2004)

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The ability of spatial transfer to occur in movement sequences is reflected upon in theoretical perspectives, but limited research has been done to verify to what extent spatial characteristics of a sequential learning task occur. Three experiments were designed to determine participants' ability to transfer a learned movement sequence to new spatial locations. A 16-element dynamic arm movement sequence was used in all experiments. The task required participants to move a horizontal lever to sequentially projected targets. Experiment 1 included 2 groups. One group practiced a pattern in which targets were located at 20, 40, 60, and 80° from the start position. The other group practiced a pattern with targets at 20, 26.67, 60, and 80°. The results indicated that participants could effectively transfer to new target configurations regardless of whether they required proportional or non-proportional spatial changes to the movement pattern. Experiment 2 assessed the effects of extended practice on proportional and non-proportional spatial transfer. The data indicated that while participants can effectively transfer to both proportional and non-proportional spatial transfer conditions after one day of practice, they are only effective at transferring to proportional transfer conditions after 4 days of practice. The results are discussed in terms of the mechanism by which

response sequences become increasingly specific over extended practice in an attempt to optimize movement production. Just as response sequences became more fluent and thus more specific with extended practice in Experiment 2, Experiment 3 tested whether this stage of specificity may occur sooner in an easier task than in a more difficult task. The 2 groups in Experiment 3 included a less difficult sequential pattern practiced over either 1 or 4 days. The results support the existence of practice improvement limitations based upon simplicity versus complexity of the task.

## **DEDICATION**

I would like to dedicate this dissertation to the love of my life, Chris Alan Braden, and to my family Daniel, Cindy, Eric, Polly, Christopher, and Danielle Wilde. They are responsible for making me a believer out of what T.S. Eliot once said, “Only those who risk going too far can possibly find out how far one can go.” My education at Texas A&M University as well as my lifelong accomplishments are a direct result of their endless love, support, and encouragement to better myself by serving others. I will always be thankful for their positive influence in my life.

## **ACKNOWLEDGEMENTS**

My career goal is to improve the quality of life for others. As a physical therapist, my patients have motivated me to pursue research and study techniques that could enhance their physical well-being. Likewise, I greatly appreciate the encouragement that I have received from my fellow physical therapists and other clinicians in the health field. Many lengthy discussions and debates among my colleagues and I have resulted in research ideas that can ultimately enhance basic acquisition of motor skills, sports training, and therapy treatments.

My full respect goes to my research committee: Dr. Charles Shea (chair), Dr. David Wright, Dr. Steven Smith, and Dr. Caroline Ketcham. Their insight and expertise in the field of motor behavior have guided my way during this process. I extend appreciation to my fellow graduate students and colleagues: Dr. Jin-Hoon Park, Young Uk Ryu, Curt Magnuson, Diala Ammar, Kirk Zihlman, and all the others who have worked with me on academic projects, data analyses, seminars, symposiums, and research presentations.

I thank the good Lord above for providing me with a father who instilled in me a positive, composed character and a mother who taught me persistence. My gratitude and love will forever go to my brothers and sister for their unrelenting support. I appreciate growing up so closely to all four of my grandparents and other extended family as they instilled in me morals, values, and admirable work ethics.

Finally, I owe my Ph.D. studies and my degree completion to Chris Alan Braden. Braden has taught me the most important things about life are to live joyfully, love deeply, pray fervently, give generously, and serve humbly.

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## CHAPTER I

### INTRODUCTION

Understanding the processes involved in the fluent production of sequential movements such as those involved in speech, handwriting, typing, drumming, or playing the piano has been the object of much scientific inquiry for a number of theoretical and applied reasons. From a theoretical perspective this class of movements is important because sequential movements are thought to be initially composed of a number of relatively independent elements, which through practice are concatenated, consolidated, or otherwise organized into what appear to be a smaller number of subsequences (termed motor chunks by Verwey, 1994). As early as 1951, Lashley proposed that sequential actions were structured such that the order of the movement elements was determined independent of the nature of the movement elements (also see Henry & Rogers, 1960; Klapp, 1995; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Schmidt, 1975; Sternberg, Knoll, & Turock, 1990). This notion of hierarchical control of movement sequences was refined as a result of a series of experiments and theoretical models by Rosenbaum and colleagues (e.g., Rosenbaum, Kenny, & Derr, 1983; Rosenbaum, Saltzman, & Kingman, 1984; Rosenbaum & Saltzman, 1984; Rosenbaum, Hindorff, & Munro, 1986; Rosenbaum, 1990) in the 1980s and 90s. These models described hierarchical control of movement sequences in terms of an inverted tree/branch metaphor such that higher levels (nodes), which were thought to transmit sequence

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This dissertation follows the style and format of the *Journal of Motor Behavior*.

information, branched into lower levels, where specific element/effector information was stored (also see Nissen & Bullemer, 1987, Povel & Collard, 1982). The internal representation of this information, which results in a stable movement structure, was thought to be retrieved, unpacked, parameterized, and/or edited (depending on the theoretical perspective) prior to execution so as to meet the specific environmental demands. These models seemed to account fairly well for, at least some of, the time delays between the discrete individual and/or grouped elements in the sequence.

While the performance and learning of movement sequences has received a good bit of experimental attention, little if any focused attention has been directed at participants' ability to transfer or modify movement sequences when faced with new environmental constraints. This is a critical practical issue because performers are often faced with the task of executing movement sequences under conditions different from those experienced during practice. The manner by which the original movement sequence is adapted is also of considerable theoretical interest because observing how performers change learned movement sequences when faced with new constraints should provide a window through which to observe the fundamental ways in which movement sequences are structured, stored, and executed. The primary long-term objective of this research is to identify the conditions under which learned movement sequences can be effectively transferred and the process whereby movement sequences are modified if they cannot be effectively transferred. By imposing new requirements on learned movement sequences, important new theoretical insights into the control and learning of movement sequences can be gained. Furthermore, determining the boundary conditions for effective transfer

and the conditions under which movement sequences can be effectively modified will allow for further *theoretical* development and may ultimately lead to more effective training and retraining protocols.

Recently, theorists have viewed the processing of sequential movement in terms independent, perhaps parallel, processing mechanisms (e.g., Keele et al., 1995; Verwey, 1994, 1996, 2001; also see Schmidt, 1975): one processing mechanism responsible for planning and organizing the elements in the sequence and the other responsible for the articulatory activities required to activate the specific effectors. Verwey (1994, 2001), for example, proposed a cognitive processor, which plans and represents the sequential organization of the action, and a motor processor, which formulates the specific commands required to carry out the desired sequence. An interesting feature of the Verwey's dual processor model is the proposal that the cognitive and motor processing mechanisms are not only independent but can operate in parallel. Thus, when a learned movement sequence is represented and executed as a series of subsequences (motor chunks), the planning of the next subsequence can be carried out while the current subsequence is being executed. Interestingly, Verwey proposed that the slower execution of subsequences in multi-subsequence movements could occur because the cognitive processor is required for high level sequence control; whereas, in single element or single subsequence movements the cognitive processor can be allocated to sequence execution. The results should be that simpler sequences that do not require the cognitive processor to be allocated to higher level processing should be executed more rapidly than the same elements in a more complex sequence where the cognitive processor is

required. This is different from other more serial dual processor models (e.g., Keele et al., 1995; Klapp, 1995, 1996; Rosenbaum, Saltzman, & Kingman, 1984; Rosenbaum & Saltzman, 1984; Schmidt, 1975) where the processing related to the sequence organization is completed prior to the initiation of the movement sequence (i.e., preprogrammed), and therefore processing at one level is relatively independent of processing at other levels.

Moreover, if sequence representation is, from a processing standpoint, independent of element production, performers should be able to effectively utilize the representation for a learned movement to produce variations of the original movement pattern. Shea and colleagues (e.g., Lai, Shea, Bruechert, & Little, 2002; Park & Shea, 2002, 2003, ; Whitacre & Shea, 2002) have demonstrated, for example, that performers can transfer a learned movement sequence, initially learned using one limb, to the contralateral limb or a different muscle group on the same limb. Remarkably, not only was the overall movement time maintained on the effector transfer test, but the movement structure (pattern of chunking sequence elements) was also preserved. Strong effector transfer results were found for relatively simple 3-element movement sequences as well as relatively complex 8- and 16-element sequences. The results of these experiments are consistent with the notion that sequence representation, at least initially, is represented in an abstract, effector independent manner. These results also suggest that movement sequences may be effectively transferred without disruption in the movement structure when other movement parameters (e.g., absolute time, absolute amplitude), besides the specific effectors, are changed.

Thus, the focus of the present experiments was to determine the extent to which movement sequences could be transferred when the spatial requirements of the sequence are changed – sequence order unchanged. It was predicted that participants can effectively transfer to new spatial requirements when the changes were proportional across the movement sequence, but not when the changes were non-proportional. Proportional in this context means that the relationships between elements in the sequence maintain the same proportional amplitudes to each other but that the overall scale of the movement sequence could be increased or decreased. Non-proportional changes involve changing the relationship between amplitudes of the elements. The movement structure that is developed over practice can be maintained in proportional transfer conditions by simply rescaling the movement sequence, but the movement structure must be altered to effectively produce a non-proportional change.

To test this hypothesis, participants completed a 16-element movement task after receiving instructions to move the arm lever as quickly and as smoothly as possible to sequentially presented targets projected onto a tabletop (Park & Shea, 2002). Initially, participants reacted to the stimuli much as they would in a choice reaction time situation, but over practice with a repeated sequence they became less reactive to the visually presented targets because they anticipated the upcoming target in the sequence. The result of acquiring sequence knowledge is an increasingly more rapid and fluid sequence production. This task was chosen because previous research (e.g., Park, Wilde & Shea, 2004) using this task demonstrated that participants “chunk” or “package” two or more elements together in such a way that the elements appear to be executed as relatively

independent subsequences. Generally these subsequences have been operationally defined as a relatively long movement time to a target (beginning of subsequence) followed by relatively short movement times to one or more of the following targets (see Nissen & Bullemer, 1987, Povel & Collard, 1982; Verwey, 1994). The delay prior to the first item in a subsequence was thought to occur because the subsequence had to be retrieved, programmed, and/or otherwise readied for execution. Subsequent elements in the subsequence are produced more rapidly than the first because processing related to their production was completed during the initial interval. Thus, the movement structure pattern of element durations that is adopted under one set of conditions can be determined so that changes, if any, can be observed on transfer tests.

Povel & Collard (1982) demonstrate various ways that participants subsequence elements in a key press task that result in faster response execution rates for those sequences that participants organize into fewer subsequences. Experiments 1 and 2 will utilize a 16-element sequence that is relatively complex. Previous research with this sequence found that participants require several practice sessions before performance asymptotes. Experiment 3 involves a 16-element arm movement sequence in which the elements were rearranged in an attempt to simplify the sequence. This was done by organizing the elements so that the movement is more rhythmical and predictable. In this context, simple and complex will be defined on the basis of the number of movement subsequences and the element durations. That is, given the same elements, equal movement amplitude, and an equal number of reversals, a sequence structured into fewer subsequences and produced more rapidly will be considered the simpler response



sequence. Further, performance on a simpler sequence should asymptote earlier in the practice phase. This latter prediction arises from the notion that development of the movement structure for the simpler sequence will require less cognitive resources to develop and more resources can be allocated to optimizing the specific motor command. The result will be a higher level of specificity.

In these experiments, as in a number of other experiments involving repeated sequences (e.g., Keele et al., 1995; Park & Shea, 2002, 2003, ), participants periodically in acquisition perform blocks involving randomly presented elements. This is done in order to determine if differences arise between groups in terms of general performance capabilities unrelated to acquiring the repeated sequence. That is, improvements over practice or differences observed on the retention or transfer tests on the random sequence indicate general task improvements while the difference between the performance on the random blocks and the repeated blocks/tests indicate improvements resulting from sequence knowledge. Most importantly, from a design standpoint, the random blocks in retention/transfer using the various amplitude combinations, provide a reference upon which to determine the extent to which sequence knowledge (and the associated response structure) contributes to the increased sequence production speed.

The proposed experiments impose new criteria onto learned movement sequences, identify conditions in which learned movement sequences are transferred, and distinguish conditions in which modifications must occur to transfer effectively. The primary purpose of the present experiments is to determine the extent to which participants can transfer a learned movement sequence to proportional and non-

proportional transfer conditions after minimal (1 day) and more extensive (4 day) practice and whether this capability differs for simple and more complex sequences.

## **CHAPTER II**

### **EXPERIMENT 1**

#### Introduction

There are many instances where a learned movement sequence must be altered to meet external demands. In signing your name on a document, for example, you may be required to produce the action so that the strokes of the pen remain within a limited space, or in a classroom situation, you may be required to sign your name on the black board large enough for the whole room to view. Likewise, a pianist or typist may be required to use a keyboard in which the distances between the keys and/or the size of the keys are different from that typically used. These conditions require the proportional rescaling of the spatial aspects of the action sequence without changing the sequence order. Rescaling may require subtle changes in the actual pattern of effector activation or even the use of different effectors. Yet, in rescaling an entire movement sequence, the higher order aspects of the movement sequence, which are reflected in the movement kinematics, presumably, can remain intact. However, it may be more disruptive if some elements in the sequence are rescaled but not others. For example, it may be more problematic to write one or two letters in your signature larger relative to the other letters than to rescale the entire sequence. Likewise, it may be more problematic to shift one key on the keyboard than shifting all the keys proportionally. These non-proportional changes may require changes in the higher order sequence structure to effectively accommodate, while this structure should remain appropriate for proportional changes.

The purpose of Experiment 1 was to determine the extent to which participants can transfer a learned movement sequence to proportional and non-proportional transfer conditions. It is predicted that participants will experience little difficulty in transferring to conditions where the changes in the spatial conditions are proportional – that is, the required movement pattern has the same shape as the one practiced, but requires proportionally smaller or larger amplitude movements. Further, it is predicted that participants will experience difficulty in transferring to non-proportional transfer conditions. Effective performance under non-proportional transfer conditions may require a different higher order sequence structure and not just the rescaling of a learned sequence structure. A non-proportional transfer condition can be constructed by changing the shape of the movement pattern – that is, rescaling some but not all of the elements comprising the sequence.

## Method

### Participants

College students (N=16), equal male and female, ages 18-28, volunteered to participate in the experiment. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. All participants were right-hand dominant as determined by self-report prior to the experiment. Informed consent was obtained prior to participation in the experiment.

### Apparatus

The apparatus consisted of a horizontal lever affixed at one end to a near frictionless vertical axle. The axle, which rotated freely in ball-bearing supports, allowed the lever to

move in the horizontal plane over the table surface. At the distal end of the lever, a vertical handle was attached. The position of the handle was adjusted so that, when the participant rested their forearm on the lever, their elbow aligned over the axis of rotation, so they could comfortably grasp the handle (palm vertical). The horizontal movement of the lever was monitored (100 Hz) by a potentiometer that was attached to the lower end of the axle. The data were used on-line to determine when target positions were achieved and were stored for later analysis on an IBM compatible computer. The targets and total movement time were displayed on the table top by a projection system mounted above the table.

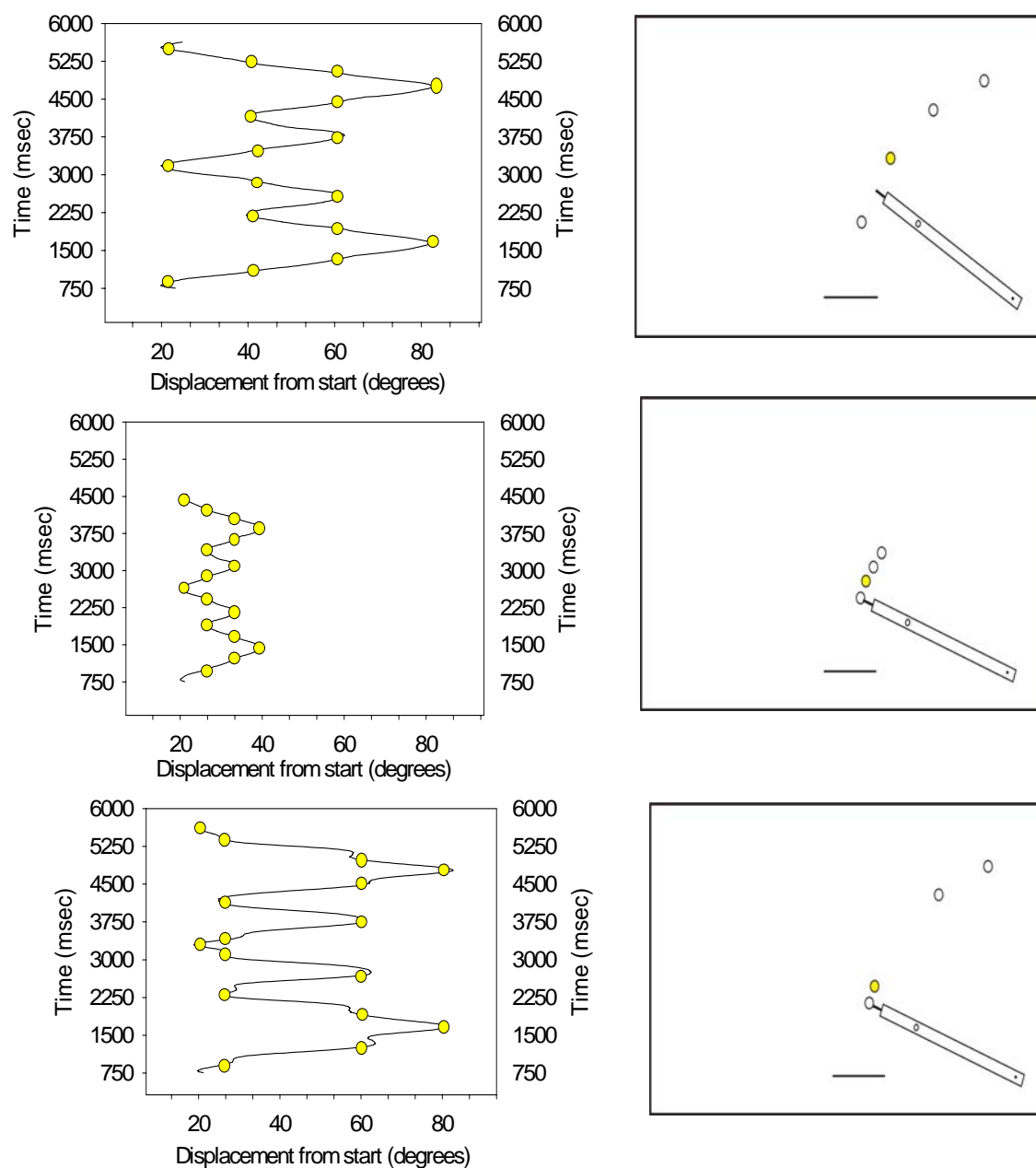
### Procedure

Prior to entering the testing room, participants were randomly assigned to one of two acquisition conditions. One practice condition used targets spaced at 20, 40, 60, and 80 degrees from the start position. This was called the long condition. The other acquisition condition used targets spaced at 20, 26.67, 60, and 80 degrees from the start position. This was labeled the mixed condition. Note that only the second target (40 vs. 26.67 degrees) was different in the two sequences.

Upon entering the testing room, participants were seated in a chair facing a table on which the apparatus was mounted. The lever apparatus was adjusted so that the participant's relative elbow angle was approximately 60 degrees at the starting position. Instructions were then given informing participants of how to perform the task. To begin each block participants were told to move the lever to the starting position (line on the table surface arbitrarily designed 0 degrees). When the start position was achieved the

outlines of the four circles (targets) were projected on the table top representing lever positions of 20, 40, 60, and 80 degrees or 20, 26.67, 60, and 80 degrees (see Figure 1, top-right and bottom right, respectively) from the start position, depending on the acquisition condition. The diameter of the targets represented 2 degrees of elbow extension/flexion. The presentation of the outlines of the targets indicated the block was about to begin. A short time later (2-5 s), a “start” tone was presented, and the first target was illuminated. Participants were instructed to move the lever as quickly as possible to the target. Upon “hitting” the target (i.e., passing into the target position) the illumination was “turned off”, and the next target was immediately illuminated until the sequence was completed. Participants were instructed to move the lever from one target to the next as quickly and smoothly as possible.

A 16-element sequence (Targets 4, 7, 10, 7, 4, 7, 4, 1, 4, 7, 4, 7, 10, 7, 4, and 1) was repeated on 12 of 16 acquisition blocks. Blocks consisted of 10 repetitions of the sequence resulting in 160 targets. The repeated sequence was used on all but Blocks 1, 5, 9, and 13. On these blocks the targets were illuminated in a random order. On all other acquisition blocks the repeated sequence was presented consecutively ten times. Participants were not provided any information about the random or repeated sequences. A rest interval of 30 s was provided after each block.



**Figure 1.** Long (top), short (middle), and mixed (bottom) 16-element sequences used in Experiment 1. The left panel illustrates displacement traces representative of those for participants on the retention/transfer tests. The right panel illustrates the manipulandum/cursor and target positions used for the respective conditions.

Three delayed retention/transfer tests (long, short, and mixed) were conducted approximately 24 hrs after the completion of the acquisition session. The basic task and sequence for the tests were the same as on day one. The long test used targets located at 20, 40, 60, and 80 degrees from the start position. This was a retention test for the long acquisition group and a transfer test for the mixed acquisition group. The short test involved targets located at 20, 26.67, 33.33, and 40 degrees (see Figure 1 right middle). This was a transfer test for both groups. More specifically, this was a proportional transfer test for the long group and a non-proportional transfer test for the mixed group. The mixed test involved targets positioned at 20, 26.67, 60, and 80 degrees. This was a retention test for the mixed acquisition group and a non-proportional transfer test for the long group. The order of the retention/transfer tests was counterbalanced. In addition three random sequence tests, one using each of the retention/transfer target configurations, were conducted. The random sequence tests were conducted approximately 5 min after the retention/transfer tests and were used as a reference for evaluating sequence performance on retention and transfer tests. The order of the random sequence tests was counterbalanced.

### Data Analysis

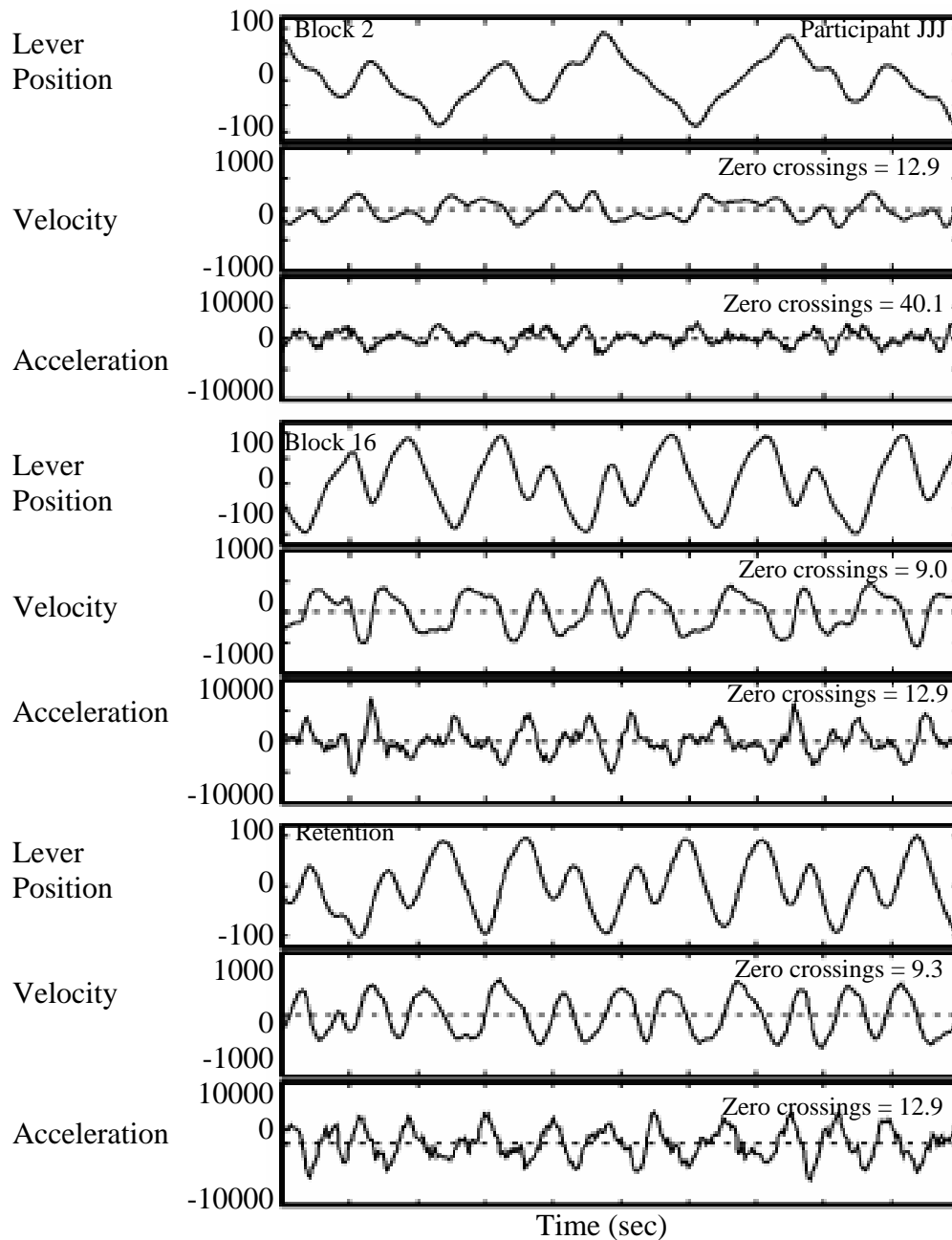
Data analysis was performed using Matlab (Mathworks, Natick, MA). The individual trial time series were used to compute lever displacement, velocity, and acceleration. To reduce noise the angular displacement time series was filtered with a 2nd order dual-pass Butterworth filter with a cutoff frequency of 10 Hz. A 3-point difference-algorithm was used to compute the velocity signal. The velocity signal was smoothed with a mobile 3-



point average algorithm before computing angular acceleration using a 3-point difference algorithm. Element response time was computed as the elapsed time from “hitting” (crossing the target boundary) the currently illuminated target to “hitting” the next illuminated target. Data analysis was identical for Experiment 1, 2, and 3.

### Results

Examples of the movement kinematics (angular displacement, velocity, and acceleration) for the long and mixed sequences during acquisition and retention are provided in Figure 2. These data illustrate that movement speed, consistency, and fluidity increase over practice with the long sequence performed somewhat more quickly and with fewer zero crossing in the acceleration record than the mixed sequence early but not later in acquisition. Zero crossings indicate momentary delays or reversals in the movement sequence and are not directly related to movement speed. In the absence of any overt transitions between elements or subsequences and assuming no movement corrections resulting in reversals, each repetition of the sequence would be minimally composed of 8 zero crossings – each zero crossing representing the prescribed reversals in the sequence. This measure characterizes the extent to which a sequence is broken down into subsequences or conversely the fluency with which the sequence is produced. The sequence and element level analyses of element durations and acceleration zero crossings are provided below.

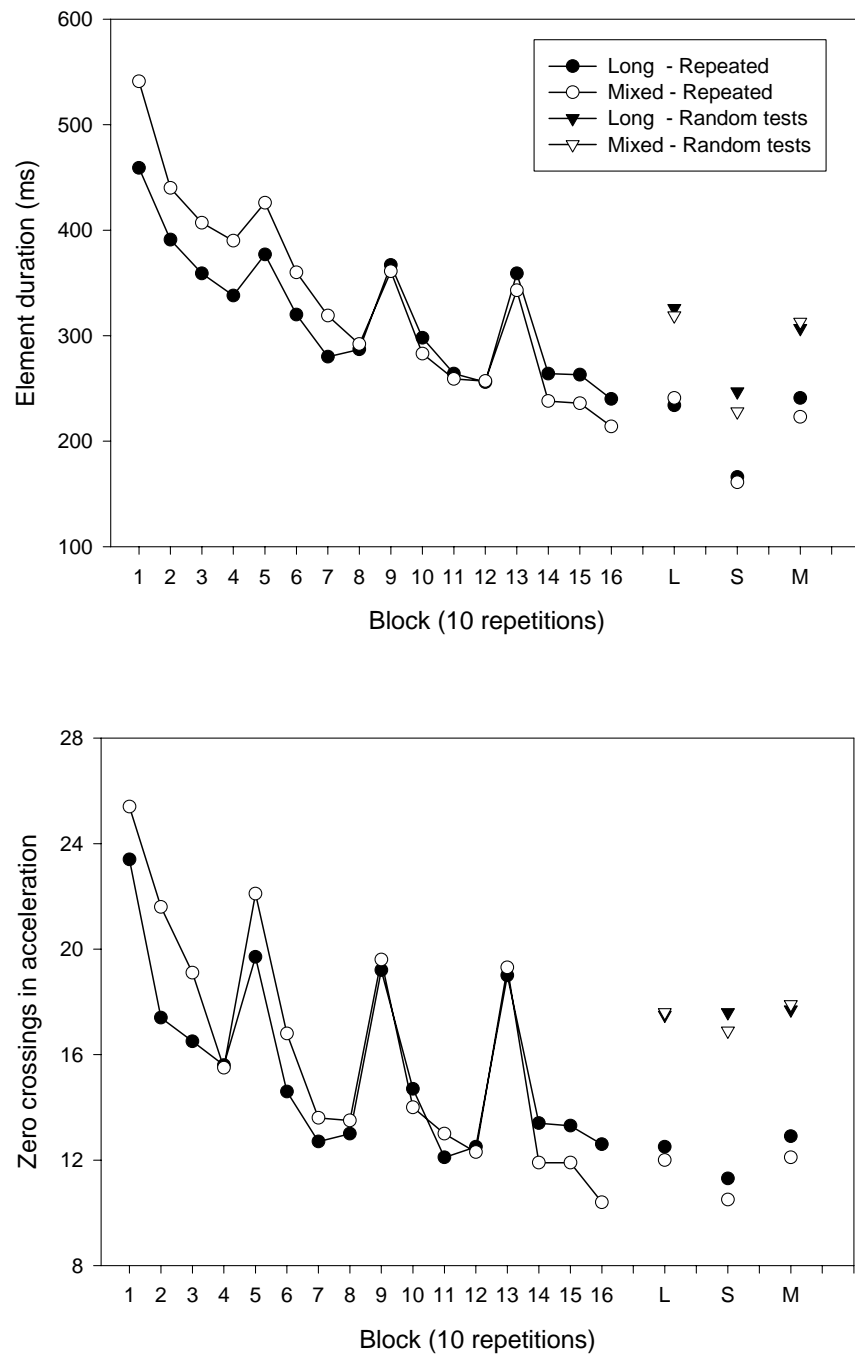


**Figure 2.** Sample position, velocity, and acceleration plots for Participant JJJ in the long sequence condition early in practice (Block 2, top), late in practice (Block 16, middle), and on the retention test (bottom). The average number of zero crossings per sequence on the velocity and acceleration plots is provided. Zero crossings were determined for each repetition of the sequence and averaged for each block. Note that 8 zero crossings would be minimally required to complete the response sequence; one for each reversal in direction. Additional zero crossings indicate additional (unnecessary) reversal and/or momentary pauses in the production of the sequence.

### Acquisition

Element duration and zero crossings on the acceleration records during acquisition were analyzed in separate 2 (Acquisition sequence - long and mixed) x Block (1-16) analysis of variance (ANOVA) with repeated measures on block. Mean element duration across acquisition and retention/transfer blocks are provided in Figure 3 (top) and zero crossings (bottom).

Sequence Level Analysis of Element Duration. There was not a significant main effect of group  $F(1,14)=2.08$ ,  $p>.05$  showing that both acquisition groups performed similarly. However, the main effect of block  $F(15,255)=39.95$ ,  $p<.01$ , was significant. Duncan's new multiple range tests on block indicated that the random blocks (Blocks 1, 5, 9, and 13) were responded to more slowly than adjacent repeated blocks. In terms of the random blocks, responses were slower in Block 1 than in Blocks 5, 9, and 13 which did not differ from each other. In terms of the repeated blocks, participants responded more slowly on Block 2 than all other repeated blocks and Blocks 3 and 4 were responded to more slowly than repeated blocks after Block 7. In addition, Blocks 6-8 and 10 were responded to more slowly than repeated blocks after Block 12. The analysis also indicated a Group x Block interaction  $F(15,255)=2.07$ ,  $p<.05$ . Simple main effects analysis confirmed that the random blocks were responded to more slowly than adjacent repeated blocks under both the long and mixed sequence conditions and that the mixed sequence was responded to more slowly than the long sequence on Blocks 1-8. The interaction accrues from the narrowing of the differences between the long and mixed sequence conditions on the repeated blocks over practice.



**Figure 3.** Mean element duration during acquisition (Blocks 1-16) and retention/transfer testing (L=long, S=short, and M=mixed sequences) in Experiment 1. The repeated sequence was presented on Blocks 2-4, 6-8, 10-12, 14-16, and on the retention and transfer blocks. Random sequences were presented on Blocks 1, 5, 9, and 13.

Sequence Level Analysis of Zero Crossings. The main effect of block  $F(15,256)=25.11$ ,  $p<.01$ , was significant. However, the analysis did not indicate a main effect of group  $F(1,14)<1$ ,  $p>.05$ . Duncan's new multiple range tests on block indicated that the random blocks (Blocks 1, 5, 9, and 13) were responded to with more zero crossings than adjacent repeated blocks. In terms of the random blocks, there were a larger number of zero crossings in Block 1 than in Blocks 5, 9, and 13 which did not differ from each other. In terms of the repeated blocks, participants produced more zero crossings on Block 2 than all other repeated blocks and Blocks 3 and 4 were responded to with more zero crossings than repeated blocks after Block 7. The analysis also indicated a Group x Block interaction  $F(15,256)=2.81$ ,  $p<.01$ . Simple main effects analysis confirmed that the random blocks were responded to with more zero crossings than adjacent repeated blocks under both the long and mixed sequence conditions and that the mixed sequence was responded to with more zero crossings than the long sequence on Blocks 2-3 and 14-16. The interaction appears to accrue from the finding that the mixed sequence was responded to with more zero crossings early in practice but fewer zero crossing late in practice as compared to the long sequence.

#### Retention and Transfer

The retention and transfer data were analyzed in two general ways. The first analysis was similar to that conducted for acquisition and was designed to determine sequence level differences between acquisition groups. The sequence level analysis was a 2 (Acquisition sequence – long and mixed) x 2 (Sequence type – random or repeated) x 3

(Test – long, mixed, short) ANOVA with repeated measures on sequence type and test. This analysis was conducted on element duration and zero crossings in acceleration. In addition, element level analyses were conducted to determine if the pattern of element duration were similar on the repeated sequence retention and transfer tests. The element level analysis, which was conducted separately for the acquisition groups, were Test (long, mixed, short) x Element (1-16) ANOVAs with repeated measures on both factors.

Sequence Level Analysis Element Duration. Participants performed the random sequences more slowly than the repeated sequences. Even though neither group had been provided practice on the short sequence, both acquisition groups performed this sequence more quickly than the other two. The analysis indicated main effects of type,  $F(1,14) = 26.05$ ,  $p < .01$ , and sequence,  $F(2,28) = 128.85$ ,  $p < .01$ . The main effect of acquisition group,  $F(1,14) = 0.03$ ,  $p > .05$ , was not significant. All interactions also failed significance.

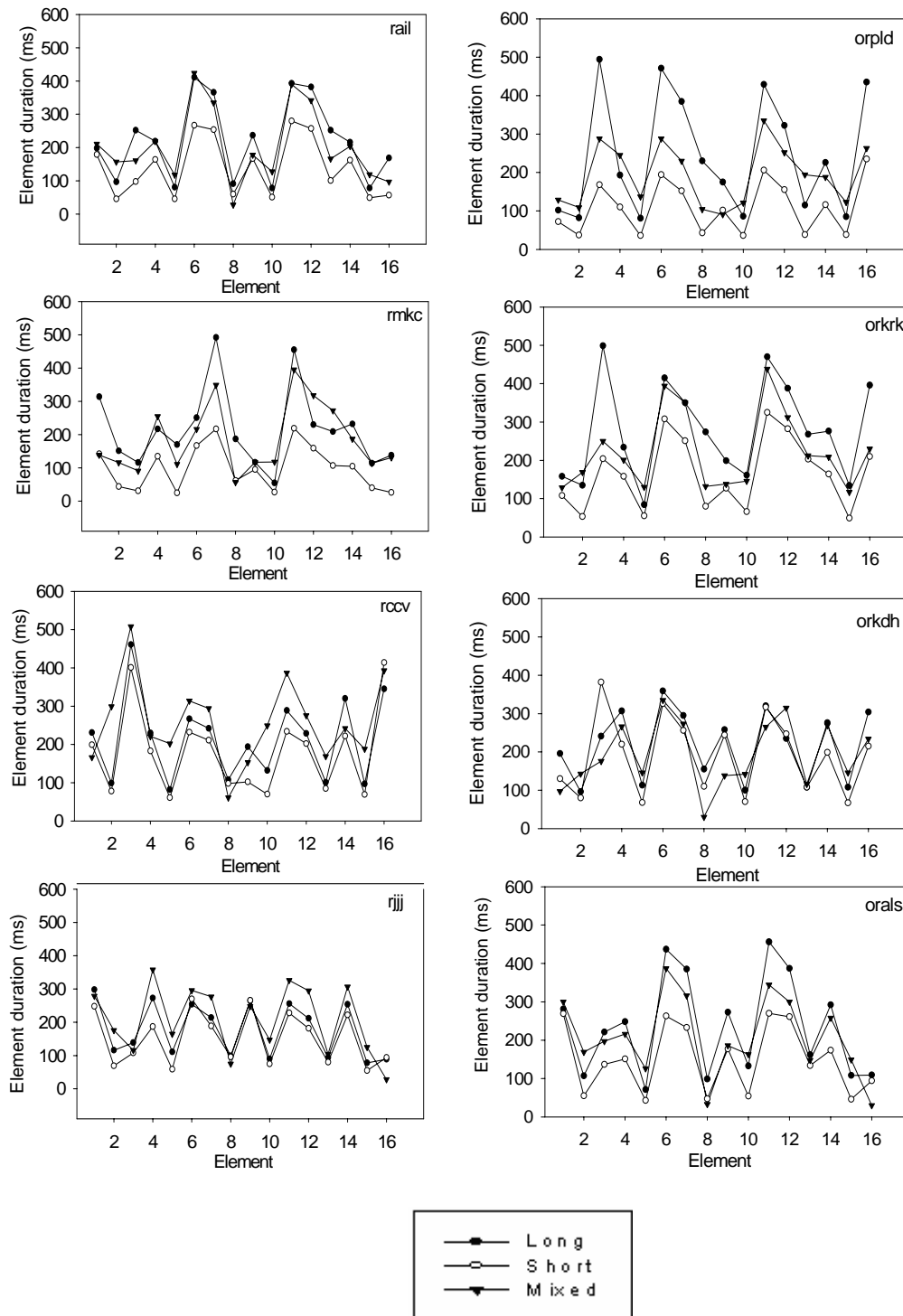
Sequence Level Analysis of Zero Crossings. Participants performed the random sequences with more zero crossings than the repeated sequences. Even though neither group had been provided practice on the short sequence, both acquisition groups performed this sequence with fewer zero crossings than the other two. The analysis indicated main effects of type,  $F(1,14) = 37.94$ ,  $p < .01$ , and sequence,  $F(2,28) = 8.16$ ,  $p < .01$ . The main effect of acquisition group,  $F(1,14) < 1$ ,  $p > .05$ , was not significant. All interaction also failed significance.

Element Level Analysis of Element Duration. The Sequence x Element ANOVA indicated main effects of sequence,  $F(2, 329) = 178.99$ ,  $p < .01$ , and element,  $F(15,329) =$

14.32,  $p < .01$ . Importantly, the Sequence x Element interaction,  $F(30,329) = 2.50$ ,  $p < .01$ , was also significant. Participants in the long acquisition group performed the long, mixed, and short repeated tests using approximately the same relative pattern of element durations although the long and mixed sequences were performed more slowly than the short pattern. Participants in the mixed acquisition group also appeared to produce a common pattern of element durations (Figure 4). The ANOVA indicated main effects of sequence,  $F(2, 329) = 356.76$ ,  $p < .01$ , and element,  $F(15,329) = 42.85$ ,  $p < .01$ . The Sequence x Element interaction,  $F(30,329) = 4.20$ ,  $p < .01$ , was also significant.

### Discussion

Participants practiced one of two repeated sequences (long and mixed) that differed in terms of the spatial locations of one of the target positions – the spatial locations of the other three targets were the same for both sequences. The sequences were also identical in terms of the number of elements, reversals, and sequence order. Although the long sequence was performed more rapidly and fluidly than the mixed sequence early in acquisition, no differences in element duration or zero crossings were detected later in practice. Importantly, the performance on the random sequence blocks resulted in substantially higher element durations and higher number of zero crossings than observed on the repeated sequence blocks. This indicates that the sequence order and associated advance planning afforded through knowledge of the sequence order on the repeated sequence blocks account for the more efficient movement production. Probability effects related to the fact that the Targets 4 and 7 each occurred three times more often in the sequences than Targets 1 and 10 were accounted for in the random



**Figure 4.** Sample element duration profiles for 4 participants in the long acquisition condition (left) and mixed acquisition condition (right) on the retention/transfer tests in Experiment 1.



sequences. That is, the random sequences were comprised of the same proportion of targets as the repeated sequences. Interestingly, performance on the random sequences improved up to Block 9 and then leveled off – this was not the case for the repeated sequence blocks where improvements continued until the end of practice.

The delayed retention and transfer tests were designed to determine the ability of the participants to produce the movement sequence practiced on Day 1 without the temporary effects related to the practice conditions or the aid of knowledge of results. Further, participants were tested on transfer sequences where the spatial locations of the targets were changed in a proportional or non-proportional manner. Although it was predicted that participants would exhibit faster and more fluid performance on the target configuration that they experienced during acquisition and on proportionally changed target configurations than on a transfer test where the targets were changed in a non-proportional manner, participants were able to effectively produce all of the test sequences. Remarkably, the group that practiced the long target configuration performed the mixed target configuration as well as the group that practiced that configuration on Day 1. Conversely, the group that practiced the mixed target configuration was able to produce the long target configuration as effectively as the group that practiced that sequence on Day 1. These results suggest a great deal of spatial flexibility in response production at this stage of practice. These results are consistent with findings of strong effector transfer after one day of practice and the notion that the motor system exhibits a great deal of flexibility early in the learning process.

Particularly interesting was the relative coherence between element duration, which reflects the speed with which the movement sequences are produced, and zero crossings in the acceleration records, which reflect the reversal and momentary lapses in acceleration in otherwise fluid movement production patterns. Park and Shea (2002) have shown that zero crossings, other than the minimal number required to accommodate the required reversals, tend to cluster around points in the sequence where participants much transition from one subsequence to another. Thus, zero crossings may play a prime role in limiting the speed with which the movement sequences can be produced.

### **CHAPTER III**

#### **EXPERIMENT 2**

##### Introduction

The notion that the pattern of performance on transfer tests changes as a result of extended practice was proposed in the modular notion of sequence processing by Keele et al. (1995; also see Wulf & Shea, 2002; Park & Shea, 2003). In addition, Jordan (1995) advocated that despite the relatively abstract nature of response sequences early in practice, further improvements in performance occur through increased precision of the motor commands, which may lead to more effector specific task characteristics than would be observed early in the learning process. Studies have demonstrated the integration of the scaling of the movement parameters, such as the specific effector and its associated feedback characteristics, into the movement plan after extended practice (Proteau, Martiniuk, Girouard, & Dugas, 1987; Proteau, Marteniuk, & Levesque, 1992).

In addition, Park and Shea (2003) recently provided additional evidence that extended practice results in increasingly specific and less effector independent response characteristics. This suggests, given additional practice, that movements become less adaptable to effector transfer conditions. However, it is not known whether the increased specificity is limited only to effector transfer or whether these limits restrict more general transfer performance. Thus, it is possible that the pattern of transfer effects, if any, observed early in practice (Experiment 1) may not be evident (or more selectively evident) after more extensive practice because the movement structure will become less adaptable to an altered spatial pattern. Alternatively, the transfer effects observed by

Park and Shea (2003) after extended practice may be limited to changes in the effectors used to produce the movement. Thus, the purpose of Experiment 2 was to determine if the pattern of transfer to new spatial requirements (proportional and non-proportional) changes as a result of extended practice. If the pattern of transfer is more restrictive after extended practice than earlier in practice, the results would suggest that the changes that occur over practice are not limited to lower level activities of the specific effectors but also to the higher level characteristics of the response. Like extended practice effects on effector transfer, it is predicted that extended practice will result in the development of increased precision and specificity of the sequential movement pattern and have detrimental effects on proportional and/or non-proportional transfer conditions.

### Method

#### Participants

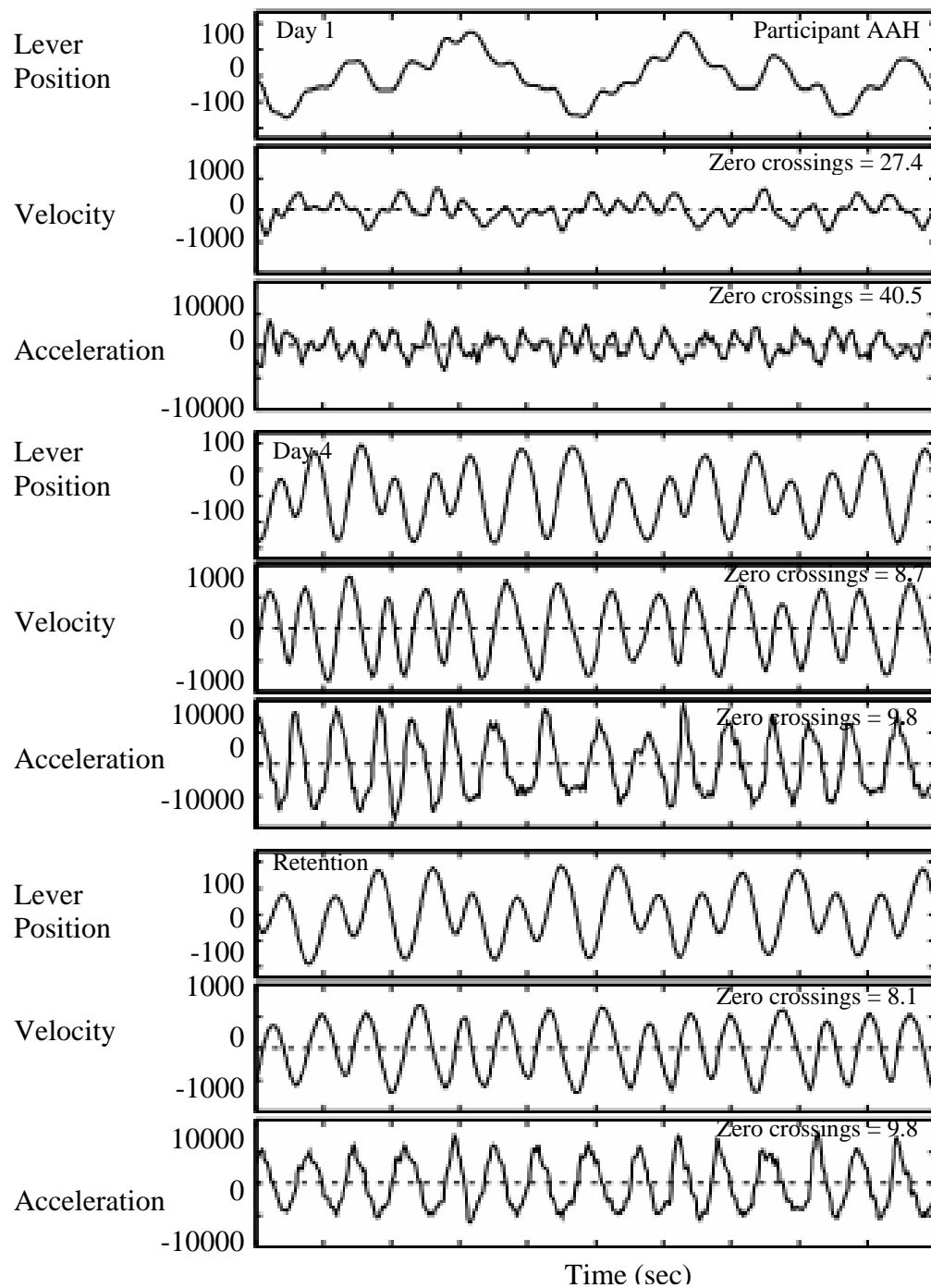
College students (N=16), equal male and female, ages 19-28, volunteered to participate in the experiment. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. All participants were right-hand dominant as determined by self-report prior to the experiment. Informed consent was obtained prior to participation in the experiment.

#### Apparatus

The apparatus was identical to that used in Experiment 1.

#### Procedure

The general procedures and sequences were identical to that used in Experiment 1. However, participants were randomly assigned to a 1-Day or 4-Day practice group. The



**Figure 5.** Sample position, velocity, and acceleration plots for Participant AAH on Day 1, 4, and 5 (retention) in Experiment 2. The average number of zero crossings per sequence is provided. Note that 8 zero crossings would be minimally required to complete the response sequence; one zero crossing for each reversal in direction. Additional zero crossings indicate additional (unnecessary) reversal and/or momentary pauses in the production of the sequence.

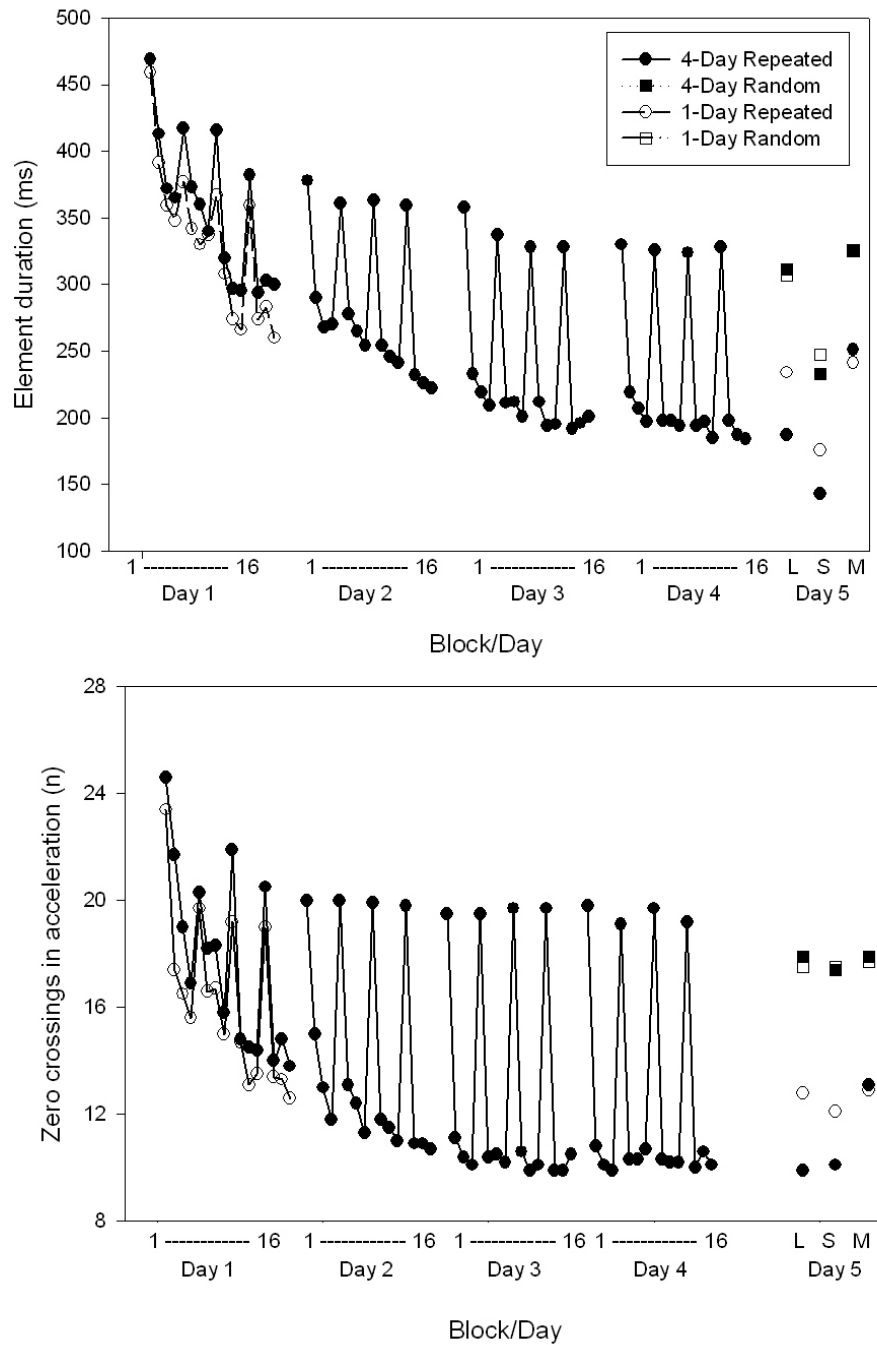
1-Day group was identical to the Long group in Experiment 1 and the 4-Day group was also treated in an identical manner with the exception that they received 3 additional days of practice (4 days total). The 16-element sequence (Targets 2, 7, 10, 7, 2, 7, 2, 1, 2, 7, 2, 7, 10, 7, 2, and 1) was complete on target spaces at 20, 40, 60, and 80 degrees from the start. The retention and transfer tests were administered approximately 24 hrs after the completion of last practice session, and the tests that were administered were identical to those used in Experiment 1.

### Results

Examples of the movement kinematics (angular displacement, velocity, and acceleration) for the long and mixed sequences during acquisition and retention are provided in Figure 5. These data illustrate that movement speed, consistency, and fluidity continue to increase over the additional days of practice. As in Experiment 1, the number of zero crossings on the acceleration record was determined. The sequence and element level analyses of element durations and acceleration zero crossings are provided below.

#### Acquisition

Mean element duration (Figure 6, top) and zero crossings in the acceleration record (Figure 6, bottom) during acquisition were analyzed in two ways. First, 2 separate (Acquisition group – 1-Day or 4-Day) x 16 (Block 1-16) ANOVAs with repeated measures on block was conducted to determine if differences on the first day of practice existed between the 1- and 4-Day acquisition groups. Second, the data for the 4-Day



**Figure 6.** Mean element duration during acquisition (Days 1-4, Blocks 1-16) and retention/transfer testing (L=long, S=short, and M=mixed sequences) in Experiment 2. The repeated sequence was presented on Blocks 2-4, 6-8, 10-12, 14-16, and on the retention and transfer blocks. Random sequences were presented on Blocks 1, 5, 9, and 13.

practice group were analyzed in a 4 (Day 1-4) x 16 (Block 1-16) ANOVA with repeated measures on both factors.

Sequence Level Analysis of Element Duration. The analysis failed to indicate main effect of group  $F(1,14)=2.08$ ,  $p>.05$ . However, the main effect of block  $F(15,255)=39.95$ ,  $p<.01$ , was significant. Duncan's new multiple range tests on block indicated that the random blocks (Blocks 1, 5, 9, and 13) were responded to more slowly than adjacent repeated blocks. In terms of the random blocks, responses were slower in Block 1 than in Blocks 5, 9, and 13 which did not differ from each other. In terms of the repeated blocks, participants responded more slowly on Block 2 than all other repeated blocks and Blocks 3-7 were responded to more slowly than repeated blocks after Block 10. The Group x Block interaction  $F(15,255)=2.07$ ,  $p>.05$ , was not significant.

The second analysis was conducted to determine if performance changes occurred across the four days of acquisition. The analysis detected main effects of day,  $F(3,441)=333.69$ ,  $p<.01$ , and block,  $F(15,441)=69.98$ ,  $p<.01$ . Duncan's new multiple range tests indicated that mean element duration significantly decreased on each of the four days of acquisition. The multiple range test on block indicated that the random blocks (Blocks 1, 5, 9, and 13) resulted in higher element durations than all repeated blocks. In addition, repeated blocks 2-7 resulted in higher element durations than observed on Blocks 10-16. The analysis also indicated a Day x Block interaction,  $F(45,441)=1.98$ ,  $p<.01$ . Simple main effect analyses on the random blocks indicated decreases in element durations across blocks on Days 1 and 2, but no further decreases were observed from Block 5 on Day 3 till the end of acquisition. Simple main effects



analysis also detected decreases in element durations across repeated blocks on all days of practice.

Sequence Level Analysis of Zero Crossings. The analysis of zero crossing for the 1- and 4-Day groups on the first day of practice failed to indicate main effect of group  $F(1,14)=1.02$ ,  $p>.05$ . However, the main effect of block  $F(15,255)=43.21$ ,  $p<.01$ , was significant. Duncan's new multiple range tests on block indicated that the random blocks (Blocks 1, 5, 9, and 13) were responded to with more zero crossings than adjacent repeated blocks. In terms of the random blocks, more zero crossings were observed in Block 1 than in Blocks 5, 9, and 13 which did not differ from each other. In terms of the repeated blocks, participants responded more slowly on Block 2 than all other repeated blocks and Blocks 3-4 were responded to more slowly than repeated blocks after Block 6. The Group x Block interaction  $F(15,255)<1$ ,  $p>.05$ , was not significant.

The second analysis detected main effects of day,  $F(3,511)=105.35$ ,  $p<.01$ , and block,  $F(15,511)=42.02$ ,  $p<.01$ . Duncan's new multiple range tests indicated that mean element duration significantly decreased on each of the four days of acquisition. The multiple range test on block indicated that the random blocks (Blocks 1, 5, 9, and 13) resulted in higher element durations than all repeated blocks. In addition, repeated Blocks 2-7 resulted in higher element durations than observed on repeated Blocks 10-16. The analysis also indicated a Day x Block interaction,  $F(45,511)=1.44$ ,  $p<.01$ . Simple main effect analyses on the random blocks indicated decreases in zero crossings across blocks on Days 1 and 2, but no further decreases were observed. Simple main effects analysis

also detected decreases in element durations across repeated blocks on Days 1 and 2 but not on Days 3 and 4.

### Retention and Transfer

The retention and transfer data were analyzed in two ways. The first analysis was similar to that conducted for acquisition and was designed to determine sequence level differences between the 1- and 4-Day acquisition groups on the repeated and random test sequences. This analysis was conducted on element duration and zero crossing. The sequence level analyses were 2 (Acquisition group – 1- and 4-Day) x 2 (Sequence type – repeated or random) x 3 (Test – long, mixed, short) ANOVA with repeated measures on sequence type and test. In addition, element level analyses were conducted to determine if the pattern of element durations were similar on the repeated sequence tests. The element level analysis, which was conducted separately for the 1- and 4-Day acquisition groups, were 3 (Test - long, mixed, short) x 16 (Element 1-16) ANOVAs with repeated measures on both factors.

Sequence Level Analysis of Element Duration. Participants performed the random sequences more slowly than the repeated sequences. Even though neither group had been provided practice on the spatial configuration required for the short sequence, both acquisition groups performed this sequence more quickly than the other two test sequences. The analysis indicated main effects of test,  $F(2,28)=115.17$ ,  $p<.01$ , and type,  $F(1,14)=74.13$ ,  $p<.01$ . The main effect of acquisition group,  $F(1,14)=1.90$ ,  $p>.05$ , was not significant. However, the Group x Test,  $F(2,28)=4.46$ ,  $p<.01$ , and the Group x Test x Type,  $F(2,28)=3.37$ ,  $p<.05$ , interactions were significant. Simple main effect analysis

failed to detect any differences between the 1- and 4-Day groups performance on the random sequence tests or between random tests. However, differences between the 1- and 4-Day groups were detected on the long and short repeated sequences, but not the mixed repeated sequence.

Sequence Level Analysis of Zero Crossings. Participants performed the random sequences with nearly twice the number of zero crossings than the repeated sequences. The additional practice on the long repeated sequence resulted in decreased zero crossings for not only the long repeated sequence but also the short repeated sequence. No benefit of the additional practice was observed on the mixed repeated test. The analysis indicated main effects of test,  $F(2,28)=4.43$ ,  $p<.05$ , and type,  $F(1,14)=75.33$ ,  $p<.01$ . The main effect of acquisition group,  $F(1,14)<1$ ,  $p>.05$ , was not significant. However, the Group x Test x Type,  $F(2,28)=4.46$ ,  $p<.05$ , interaction was significant. Simple main effect analysis failed to detect any differences between the 1- and 4-Day groups performance on the random sequence tests. However, differences between the 1- and 4-Day groups were detected on the long, short, but not the mixed repeated sequences.

Element Level Analysis of Element Duration. Participants in the 1-Day acquisition group performed the long and short repeated tests using approximately the same relative pattern of element durations although the long and mixed sequences were performed more slowly than the short pattern. The mixed pattern, although requiring a non-proportional movement pattern, did not deviate from the other two. The analysis indicated main effects of test,  $F(2,329)=38.87$ ,  $p<.01$ , and element,  $F(15,329)=10.64$ ,

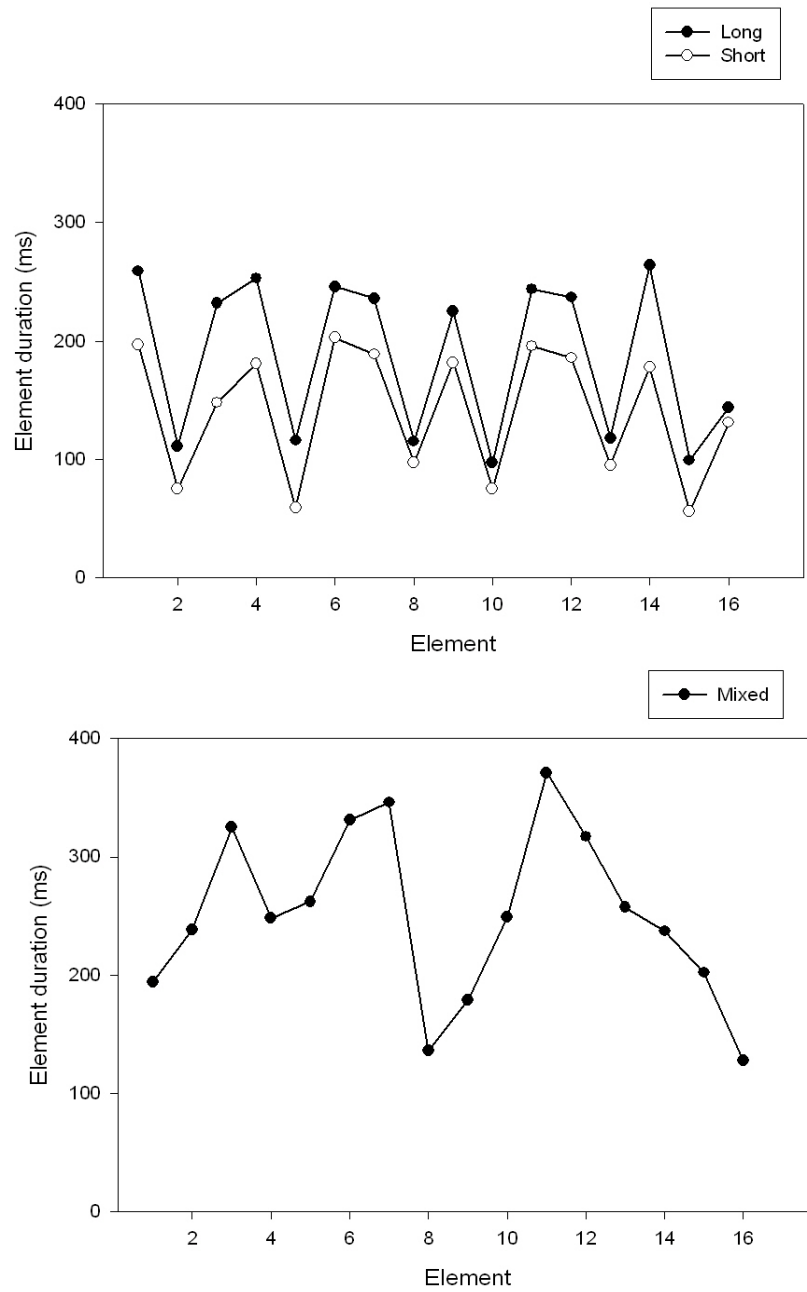
$p < .01$ . Importantly, the Test  $\times$  Element interaction,  $F(30,329)=2.29$ ,  $p < .01$ , was also significant.

Participants in the 4-Day acquisition group did not appear to produce a common pattern of element durations on the three repeated test sequences. The ANOVA indicated main effects of test,  $F(2,329)=119.48$ ,  $p < .01$ , and element,  $F(15,329)=21.92$ ,  $p < .01$ . The Test  $\times$  Element interaction,  $F(30,329)=5.04$ ,  $p < .01$ , was also significant. Simple main effects analysis indicated that similar movement patterns were used for the long and short spatial configurations, but not for the mixed sequence configuration (Figure 7).

### Discussion

Participants practiced the long movement sequence used in Experiment 1 for either 1 day (160 repetitions of the sequence/ 2560 targets) or 4 days (640 repetitions of the sequence/10,240 targets). The 1-Day group was included in order to replicate the findings from Experiment 1, assure that there were no fundamental differences between groups, and to provide a baseline from which to assess the improvements that accrue with additional practice. The sequence and element level acquisition results after 1 day of practice very closely replicated the acquisition findings from Experiment 1 and failed to detect any differences between the 1- and 4-Day groups on repeated or random tests.

The retention and transfer results of Experiment 1 indicated great flexibility in adapting the movement sequence to changes in spatial requirements. Contrary to the initial predictions, this ability was not limited to proportional transfer conditions but was equally evident on the non-proportional transfer sequence. The primary objective of Experiment 2 was to determine if this pattern of results would be replicated by the 1-Day



**Figure 7.** Average element duration profiles for participants in the 4-Day acquisition condition on the retention/transfer tests in Experiment 2. The top panel illustrates element duration profiles on the long and short sequences. The bottom panel illustrates the element duration profiles for the mixed sequence.

group and whether this flexibility persisted after 4 days of practice. As in acquisition the retention and transfer results of the 1-Day group closely replicated the retention and transfer results from Experiment 1. After only 1 day of practice participants could effectively transfer from the long spatial configuration to both the mixed and short spatial configurations. Thus, it appears clear that at this stage of practice participants utilize an abstract sequence representation that is not dependent on specific effector commands or otherwise optimized in specific ways. This finding is consistent with recent research on effector transfer (e.g., Lai et al., 2002; Park & Shea, 2002; Whitacre & Shea, 2002) and demonstrations that movement production flexibility is not limited to changes in effector (e.g., Park, Wilde, & Shea, 2004; Shapiro, 1977; Whitacre & Shea, 2000), but rather that the perceptual motor system exhibits a great deal of flexibility/adaptability early in practice.

The delayed retention and transfer test results of the 4-Day group, however, indicated a different pattern of transfer. Substantial improvements resulting from the additional practice with the long configuration were observed on the retention test and the short transfer test, but not on the mixed transfer test. Importantly, the short transfer test, where improvements occurred, was considered a proportional transfer condition because the transitions between consecutive targets were all reduced by the same amplitude (from 20 degrees to 6.67 degrees). It was initially hypothesized that participants would be capable of this type of transfer because the higher order processes that define the movement sequences could be rescaled to meet the transfer requirements. Alternatively, participants in the 4-Day group were relatively ineffective in producing

the mixed transfer sequence where the positions of the targets were changed in a non-proportional manner. Indeed, the difference between the 1- and 4-Day groups on the mixed transfer test was not significant. That is, additional practice with the long spatial configuration resulted in additional improvements both in terms of movement speed and movement fluency for the proportional transfer condition, but not in the non-proportional transfer condition.

## **CHAPTER IV**

### **EXPERIMENT 3**

#### Introduction

A number of researchers (e.g., Povel & Collard, 1982; Rosenbaum, Kenny, & Derr, 1983; Rosenbaum, Saltzman, & Kingman, 1984; Rosenbaum & Saltzman, 1984; Wilde, Magnuson, & Shea, 2004) have demonstrated that the way in which individual movement elements are hierarchically organized or “chunked” can play an important role in determining how effective the sequence is produced. Given the same elements, responses organized into fewer subsequences typically result in faster movement times, and thus, are considered easier, relative to responses comprised of more subsequences. Povel and Collard (1982), for example, demonstrated that 6-element key press sequences were chunked into 2 or 3 subsequences depending on the order in which the elements in the sequence were arranged. Accordingly, the 2 subsequence responses were executed substantially faster than the 3 subsequence response sequences. This result was recently replicated by Wilde et al. (2004) and is consistent with recent findings by Park and colleagues (2003), using arm movement sequences.

In addition, Wright and Shea (2001) predicted that decreasing the difficulty of the response structure would allow additional cognitive/motor resources to be “freed-up”. These resources could be reallocated from organizing the response structure to refining the motor commands that produce the individual elements. The notion that cognitive resources can be reallocated to assist in the element production in simple movement sequences has been proposed by Verwey (2001). If this is the case, refinements in motor



commands (Jordan, 1995; Park & Shea, 2003) would be expected to occur earlier in practice when the response structure is simpler and later when the response structure is more complex. This proposal, which also suggests that the movement structure should be developed prior to specific enhancement to the direct movement commands, is also consistent with the findings of Lai et al. (2002). They found that practice conditions that facilitated the development of the response structure should occur before practice that is aimed at enhancing movement parameters. Clearly, the time course for the learning progression for simple response sequences may not be the same for more complex motor sequences (also see Wulf & Shea, 2002, for a review of simple and complex skill learning).

Experiment 2 found that a 16-element response sequence became increasingly specific over extended periods of practice such that the benefits of additional practice were only observed on the specific task practiced and not on transfer tests. It was hypothesized that the increased specificity of the sequence production was a result of attempts by the performer to optimize movement production. Presumably, the process of optimizing the motoric aspects of the sequence was not possible earlier in practice because it was necessary to first learn the sequence order and develop the sequence structure. Experiment 3 was designed to assess whether a “less difficult/easy” sequence, a sequence that could be organized into fewer subsequences and performed more rapidly, could be effectively structured earlier in practice. If the sequence order and organization of subsequences were completed earlier, the optimization process would also begin

earlier in practice. One result would be that increased movement specificity would also be observed earlier in practice.

To test this notion, two groups, which were differentiated in terms of the amount of practice provided (1 or 4 days), attempted to learn a sequence that was designed using the same elements as in the earlier experiments but with elements arranged so that the pattern included essentially two repeated sequences. This sequence order would likely be more quickly acquired and the sequence more quickly produced than the sequences used in earlier experiments. Given the same elements, the same total movement displacement, and the same number of reversals as the prior experiments, it is hypothesized this “simpler” sequence could be structured into fewer subsequences due to the arrangement of elements in the sequence. This “simpler” sequence was also more symmetrical containing predictable, paired movement amplitudes. Thus, it is predicted that the “simpler” sequential pattern would be learned more quickly, organized into fewer subsequences, and would be produced faster than the sequences used in Experiments 1 and 2. Importantly, if participants developed sequence structure with less practice than the prior experiments, then the optimization process would also begin early in the practice phase. This latter prediction arises from the notion that development of the movement structure for the simpler sequence will require less cognitive resources to develop and more resources can be allocated to optimizing the specific motor commands. The result would be a higher level of specificity after one day of practice with the “simpler” sequence and, accordingly, a reduced ability to transfer task performance to a different spatial pattern.

More specifically, it is predicted that the movement structure for the simple sequence will be learned more quickly than that of a “more difficult” sequence such as in Experiments 1 and 2. The “simpler” pattern will likely result in faster learning of the sequence order and a faster development of the sequence structure. This will allow additional resources to focus on optimizing the specific characteristics of the motor commands. It is expected that the simple sequence will be produced more quickly both during the acquisition and retention testing phases of the experiment. It is anticipated that participants who have practiced the simple sequence for only 1 day will not be able to perform the non-proportional transfer test as well as the retention test (practiced task). This prediction is contrary to the findings for the more difficult sequence. This prediction, however, arises from the notion that development of the movement structure for the “simpler” sequence will require less cognitive resources to develop and more resources can be allocated to optimizing the specific motor command. The result will be a higher level of specificity on the practiced task, but a decreased ability to perform non-proportional transfer tasks.

## Method

### Participants

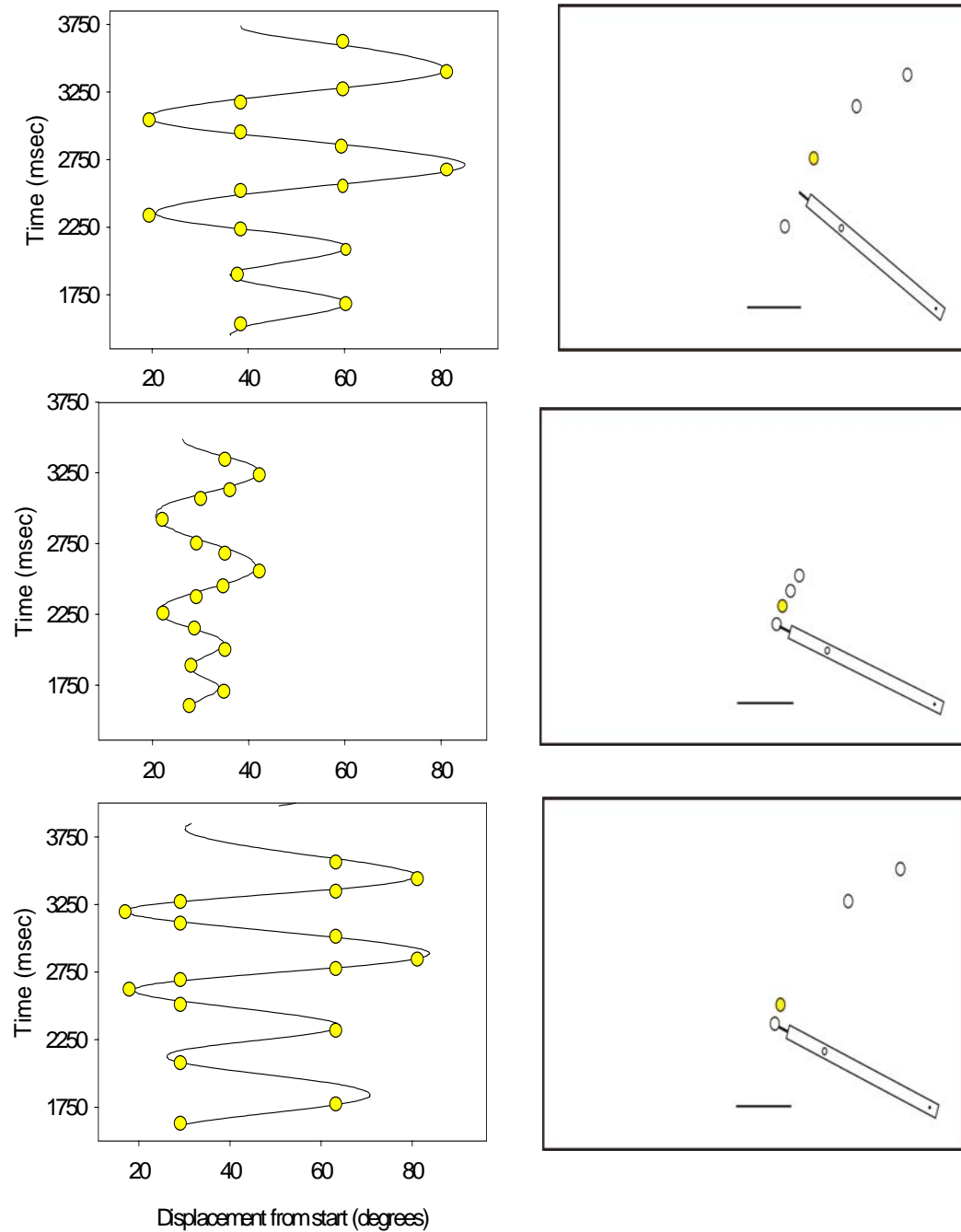
College student (N=20) volunteers, equal male and female, ages 18-28, participated in the experiment. The participants had no prior experience with the experimental task and were not aware of the specific purpose of the study. All participants were right-hand dominant as determined by self-report prior to the experiment. Informed consent was obtained prior to participation.

### Apparatus

The apparatus is identical to that used in Experiment 1. For Experiment 3, 2 groups learned a “simpler” movement pattern, with a sequence containing paired, predictable movement amplitudes designed to be subsequenced or grouped into fewer chunks than the “more difficult” sequential pattern of Experiments 1 and 2. Group 1 performed the “simpler” pattern in 1 day of practice. Group 2 performed the “simpler” pattern practicing 4 consecutive days. Both groups were tested upon completion of practice with a 24-hour delayed retention test, 2 transfer tests, and their equivalent random sequence tests.

### Procedure

Prior to entering the testing room, participants were randomly assigned to a 1-Day or a 4-Day practice group. The acquisition, retention, and transfer testing protocols were similar to that used in Experiment 1. The 1-Day group was identical to the 4-Day group with the exception that the 4-Day group received 3 additional days of practice (4 days total). Both groups practiced a “simple,” rhythmical sequence (Targets 4, 7, 4, 7, 4, 7, 10, 7, 4, 1, 4, 7, 10, 7, 4, 1). This sequence is illustrated in Figure 8. As in the earlier experiments, random sequence blocks were interspersed during acquisition and tested as equivalents to each retention/transfer phase. One day of practice (16 blocks of 160 targets) was provided for Group 1, and 4 days of practice (64 total blocks of 160 targets per block) were provided for Group 2 with the retention and transfer tests administered 24 hours after the completion of the last practice block. The retention test required



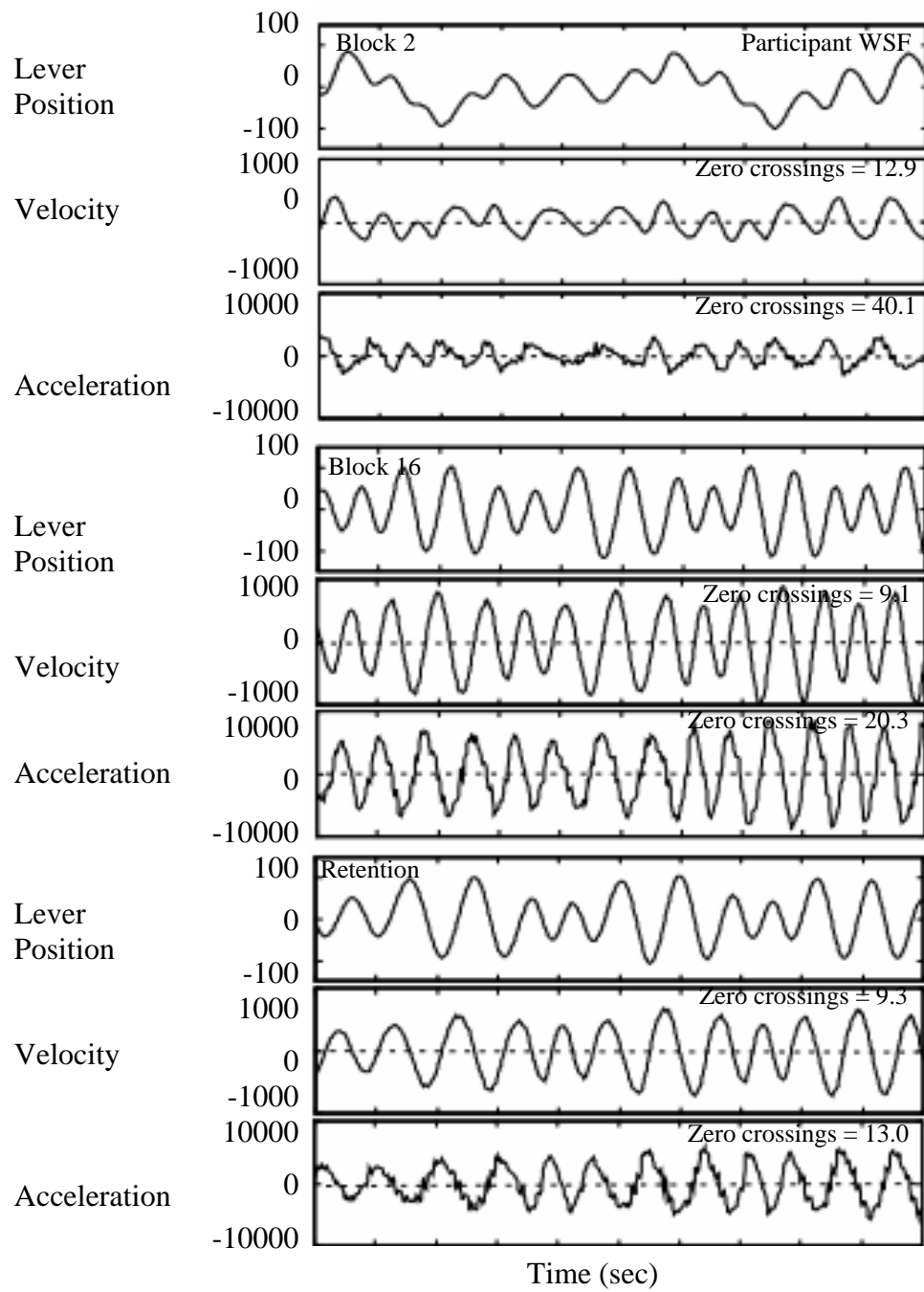
**Figure 8.** Long (top), short (middle), and mixed (bottom) 16-element sequences used in Experiment 3. The left panel illustrates displacement traces representative of retention/transfer tests. The right panel illustrates the manipulandum/cursor and target positions used for the respective conditions.

participants to produce the sequence order and spatial target locations used during practice as quickly as possible without feedback of total execution time.

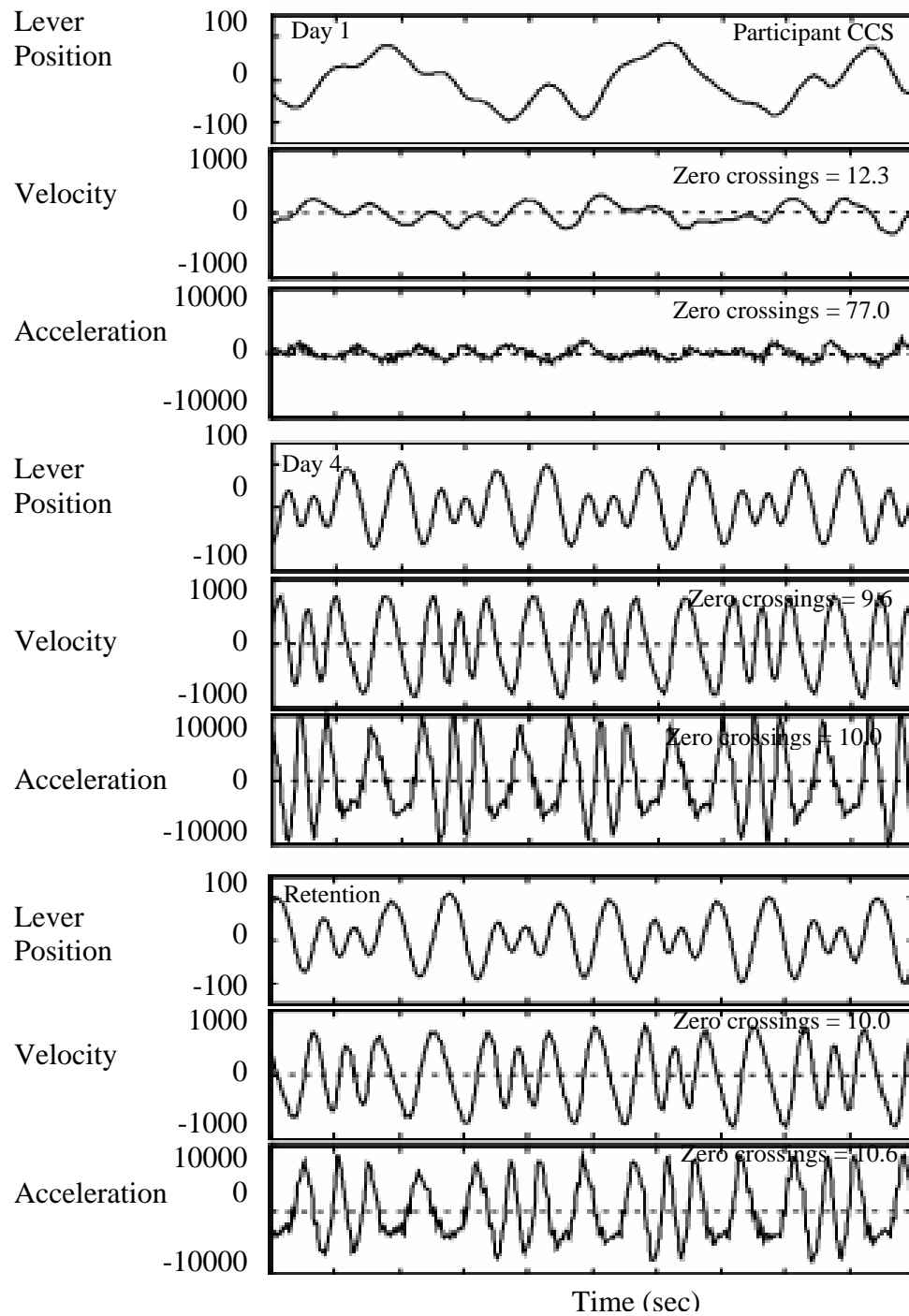
The transfer tests consisted of a proportional/ “easy” short and a non-proportional/ “easy” mixed sequence test phase. The proportional transfer test was the same simple pattern, but a proportionally compressed condition such that the displacement between targets was 6.67 degrees rather than the 20 degrees between targets as during acquisition and retention testing (Figure 8, middle). Another transfer test included the “easy” mixed version of the same pattern creating a non-proportional spatial transfer in that the second target was displaced nearer the first target to create an asymmetrical/nonproportional distance between targets as in Experiment 1. An equivalent random sequence test was conducted for each of the retention and transfer tests using the respective target configurations at either 6.67 degrees or 20 degrees. The random sequence tests were used to provide a baseline for assessing improvements in performance due to the sequence knowledge acquired over practice versus improvements due to physically practicing the task.

### Results

Examples of the movement kinematics (angular displacement, velocity, and acceleration) for the “easy” long sequences during acquisition and retention are provided in Figure 9 for the 1-day practice group and in Figure 10 for the 4-day, extended practice group. These data illustrate that movement speed, consistency, and fluidity continue to increase over the additional days of practice. As in Experiment 1, Experiment 3 zero



**Figure 9.** Sample plots for Participant WSF in the simple sequence condition early in practice (Block 2, top), late in practice (Block 16, middle), and on the retention test (bottom). Note that 8 zero crossings would be minimally required to complete the response sequence; one for each reversal in direction. Additional zero crossings indicate unnecessary reversal and/or momentary pauses.



**Figure 10.** Sample plots for Participant CCS on Day 1, 4, and 5 (retention) in Experiment 3. Note that 8 zero crossings would be minimally required to complete the response sequence; one zero crossing for each reversal direction. Additional zero crossings indicate unnecessary reversal or momentary pauses in sequence production.

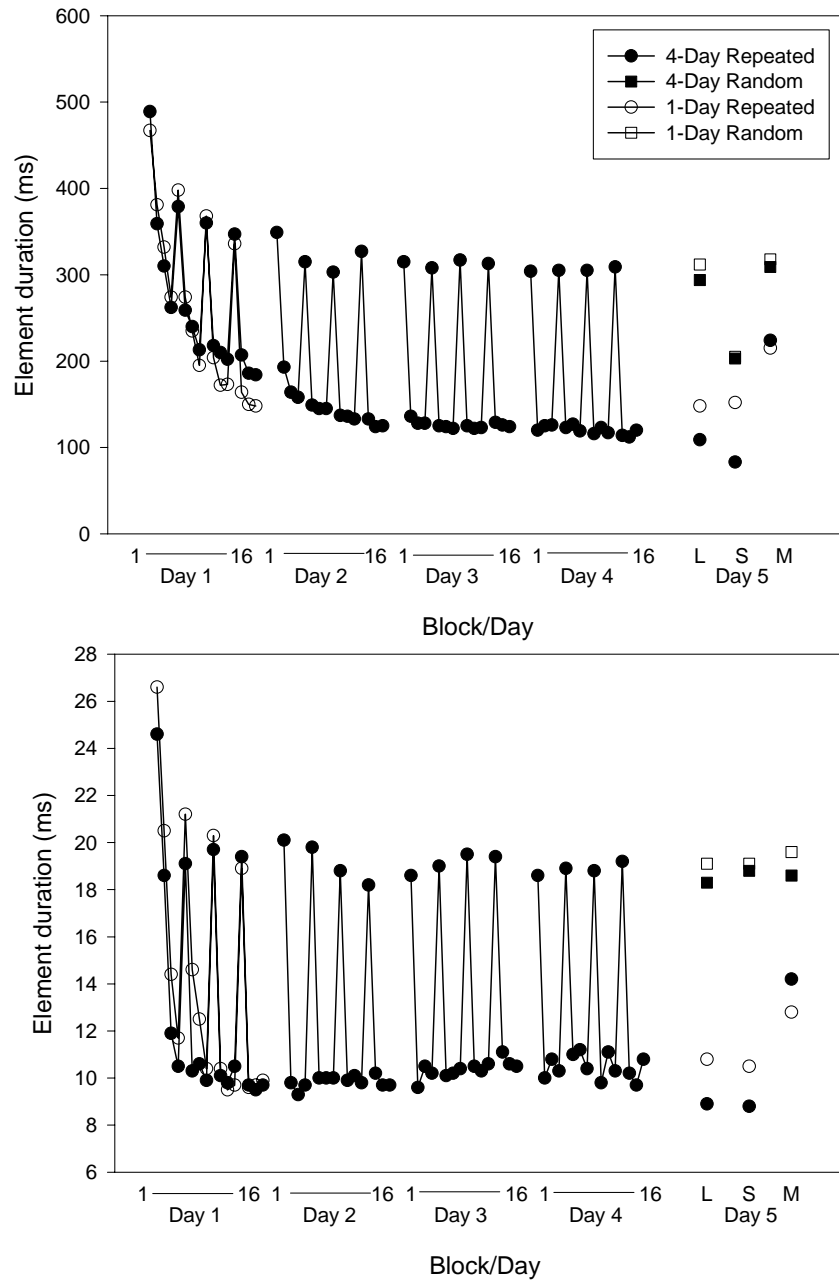


crossings are included on Figures 9 and 10 . The sequence and element level analyses of element durations and acceleration zero crossings were also determined.

### Acquisition

Mean element duration (Figure 11, top) and zero crossings in the acceleration record (Figure 11, bottom) during acquisition were analyzed in two ways. First, 2 separate (Acquisition group – 1-Day or 4-Day) x 16 (Block 1-16) ANOVAs with repeated measures on block were conducted to determine if differences on the first day of practice existed between the 1- and 4-Day acquisition groups. Second, the data for the 4-Day practice group were analyzed in a 4 (Day 1-4) x 16 (Block 1-16) ANOVA with repeated measures on both factors.

Sequence Level Analysis of Element Duration. The analysis failed to indicate main effect of group  $F(1,14)=2.08$ ,  $p>.05$  to indicate similar performance of the 2 acquisition groups. However, the main effect of block  $F(15,255)=39.95$ ,  $p<.01$ , was significant. Duncan's new multiple range tests on block indicated that the random blocks (Blocks 1, 5, 9, and 13) were responded to more slowly than adjacent repeated blocks. In terms of the random blocks, responses were slower in Block 1 than in Blocks 5, 9, and 13 which did not differ from each other. In terms of the repeated blocks, participants responded more slowly on Block 2 than all other repeated blocks and Blocks 3-7 were responded to more slowly than repeated blocks after Block 10. The Group x Block interaction  $F(15,255)=2.07$ ,  $p>.05$ , was not significant. The second analysis was conducted to determine if performance changes occurred across the 4 days of acquisition. The analysis detected main effects of day,  $F(3,441)=333.69$ ,  $p<.01$ , and block,  $F(15,441)=69.98$ ,



**Figure 11.** Mean element duration during acquisition (Days 1-4, Blocks 1-16) and retention/transfer testing (L=long, S=short, and M=mixed sequences) in Experiment 3. The repeated sequence was presented on Blocks 2-4, 6-8, 10-12, 14-16, and on the retention and transfer blocks. Random sequences were presented on Blocks 1, 5, 9, and 13.

$p < .01$ . Duncan's new multiple range tests indicated that mean element duration significantly decreased on each of the four days of acquisition. The multiple range test on block indicated that the random blocks (Blocks 1, 5, 9, and 13) resulted in higher element durations than all repeated blocks. In addition, repeated blocks 2-7 resulted in higher element durations than observed on Blocks 10-16. The analysis also indicated a Day x Block interaction,  $F(45,441)=1.98$ ,  $p < .01$ . Simple main effect analyses on the random blocks indicated decreases in element durations across blocks on Days 1 and 2, but no further decreases were observed from Block 5 on Day 3 until the end of acquisition. Simple main effects analysis also detected decreases in element durations across repeated blocks on all days of practice.

Sequence Level Analysis of Zero Crossings. The analysis of zero crossings for the 1- and 4-Day groups on the first day of practice failed to indicate main effect of group  $F(1,14)=1.52$ ,  $p > .05$  to indicate similar performances by the 2 acquisition groups at this time in practice. However, the main effect of block  $F(15,255)=62.36$ ,  $p < .01$ , was significant. Duncan's new multiple range tests on block indicated that the random blocks (Blocks 1, 5, 9, and 13) were responded to with more zero crossings than adjacent repeated blocks except Block 2. In terms of the random blocks, more zero crossings were observed in Block 1 than in Blocks 5, 9, and 13 which did not differ from each other. In terms of the repeated blocks, participants responded more slowly on Block 2 than all other repeated blocks. Blocks 3-7 were responded to more slowly than repeated blocks after Block 8. The Group x Block interaction  $F(15,255) < 1$ ,  $p > .05$ , was not significant.

The second analysis detected main effects of day,  $F(3,511)=11.99$ ,  $p<.01$ , and block,  $F(15,511)=88.82$ ,  $p<.01$ . Duncan's new multiple range tests indicated that zero crossings significantly decreased from Day 1 to Day 2 with no further decrease thereafter. The multiple range test on block indicated that the random blocks (Blocks 1, 5, 9, and 13) resulted in higher element durations than all repeated blocks. There were no differences in the repeated blocks.

### Retention and Transfer

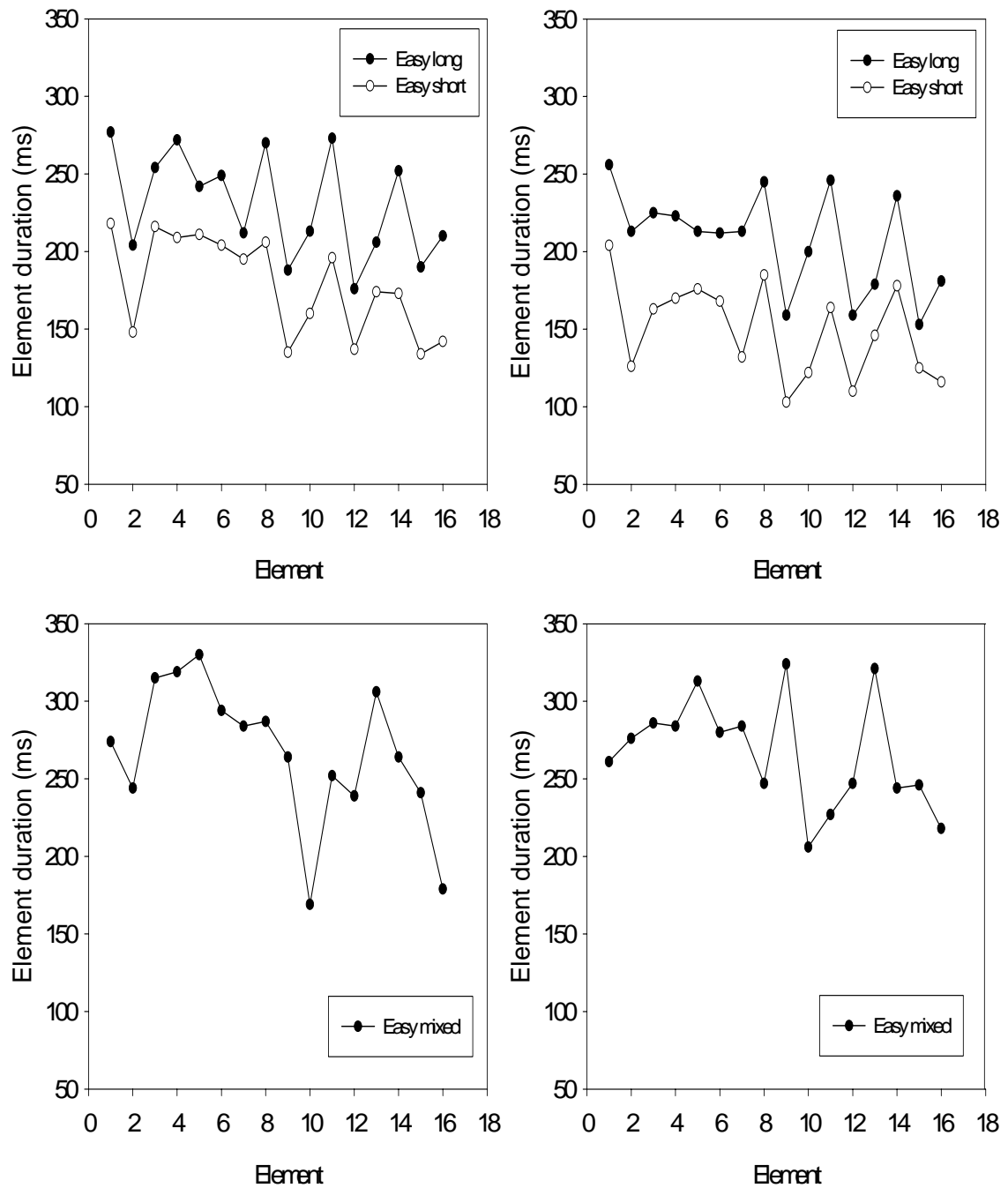
Sequence Level Analysis of Element Duration. Participants performed the random sequences more slowly than the repeated sequences. While additional practice enhanced performance on the "easy" long and the "easy" short sequences, the additional practice did not benefit performance on the "easy" mixed sequence or any of the random blocks. The analysis indicated main effects of test,  $F(2,28)=56.05$ ,  $p<.01$ , and type,  $F(1,14)=78.37$ ,  $p<.01$ . The main effect of acquisition group,  $F(1,14)<1$ ,  $p>.05$ , was not significant. However, the Test x Type,  $F(2,28)=11.98$ ,  $p<.01$ , and the Group x Test x Type,  $F(2,28)=3.75$ ,  $p<.05$ , interactions were significant. Simple main effect analysis failed to detect any differences between the 1- and 4-Day groups for performance on the random sequence tests. However, differences between the 1- and 4-Day groups were detected on the "easy" long and "easy" short repeated sequences, but not the easy "mixed" repeated sequence.

Sequence Level Analysis of Zero Crossings. Participants performed the random sequences with nearly twice the number of zero crossings than the repeated sequences. The additional practice on the "easy" long repeated sequence resulted in decreased zero

crossings for not only the “easy” long repeated sequence but also the “easy” short repeated sequence. No benefit of the additional practice was observed on the “easy” mixed repeated test. The analysis indicated main effects of test,  $F(2,28)=4.43$ ,  $p<.05$ , and type,  $F(1,14)=75.33$ ,  $p<.01$ . The main effect of acquisition group,  $F(1,14)<1$ ,  $p>.05$ , was not significant. However, the Group x Test x Type,  $F(2,28)=4.46$ ,  $p<.05$ , interaction was significant. Simple main effect analysis failed to detect any differences between the 1- and 4-Day group performance on the random sequence tests. However, differences between the 1- and 4-Day groups were detected on the long and short, but not the mixed repeated “easy” sequences.

Element Level Analysis of Element Duration. Participants in the 1-Day acquisition group performed the long and short repeated tests using approximately the same relative pattern of element durations although the long sequence was performed more slowly than the short sequence. The mixed pattern, however, was produced more slowly and was not produced using the same pattern of element durations as the long and short sequences. The analysis indicated main effects of test,  $F(2,329)=154.92$ ,  $p<.01$ , and element,  $F(15,329)=15.71$ ,  $p<.01$ . Importantly, the Test x Element interaction,  $F(30,329)=2.71$ ,  $p<.01$ , was also significant.

Participants in the 4-Day acquisition group did not appear to produce a common pattern of element durations for all three repeated test sequences. Although practice increased the speed with which the long and short sequences could be produced, the pattern of element durations used after 1 day of practice were similar to that used after 4



**Figure 12.** Average element duration profiles for participants in the 4-Day acquisition condition on the retention/transfer tests in Experiment 3. The top panel illustrates element duration profiles on the long and short sequences. The bottom panel illustrates the element duration profiles for the mixed sequence.

days of practice. The ANOVA indicated main effects of test,  $F(2,329)=360.32$ ,  $p<.01$ , and element,  $F(15,329)=9.67$ ,  $p<.01$ . The Test x Element interaction,  $F(30,329)=5.34$ ,  $p<.01$ , was also significant. Simple main effects analysis indicated that participants performed the long and short repeated tests using approximately the same relative patterns for both the long and short spatial configurations but not for the mixed sequence movement configuration (Figure 12).

### Discussion

Participants practiced the simple movement sequence for either 1 day (160 repetitions of the sequence/ 2560 targets) or 4 days (640 repetitions of the sequence/10,240 targets). The 1-Day group was included in order to provide a baseline from which to assess the improvements that may occur with additional practice. The sequence and element level acquisition results after 1 day of practice failed to detect any differences between the 1- and 4-Day groups on repeated or random tests.

The retention and transfer results of the 1-Day practice group indicated limited flexibility in adapting the movement sequence to changes in spatial requirements. As opposed to Experiment 1 results, Experiment 3 participants completed the “easy” long and short sequences but were not as successful at completing the “easy” mixed pattern. The primary objective of Experiment 3 was to determine if a “simpler” pattern produced similar trends as the “more complex” pattern demonstrated in Experiment 2, that is, a diminished flexibility regarding motor sequencing completion with practice. The retention and transfer results of participants in Experiment 3 demonstrated their ability to effectively transfer from the “easy” long spatial configuration practiced to the “easy”

short spatial configuration but not to the “easy” mixed spatial configuration after either 1 or 4 days of practice. Thus, it appears that in as early as the initial stages of practice in “simpler” sequencing tasks, the specifics of the movement structure become tightly linked to the elements such that a change non-proportionally in target spatial configuration results in poor transfer ability. This finding is consistent with recent predictions by Shea & Wulf (2004) that completing relatively “easier” motor skills results in different learning principles than “more complex” skills. The authors further describe the idea that the more complexity in a task the more information processing and practice that are likely to be required for that task to become specific. The principles regulating generalizeable qualities of actions may indeed change over practice, and this change appears to occur even earlier with “simpler” motor tasks learned by the participants. Therefore, limited flexibility regarding sequence learning forms at initial stages of practice with the “easier” task. This limited flexibility results in a sequence representation dependent on specific effector commands that creates optimization in specific ways.



## CHAPTER V

### GENERAL DISCUSSION

The primary purpose of the present experiments was to determine the extent to which a response sequence learned under one spatial configuration could be effectively transferred to an unpracticed spatial configuration and whether the ability to transfer was mediated by the amount of practice or the complexity of the sequential pattern. More specifically, it is predicted, based on results of motor program theory research on parameter transfer (e.g., Shapiro, 1977; Whitacre & Shea, 2000) and recent effector transfer research using both simple (e.g., Lai et al., 2002; Whitacre & Shea, 2002) and more complex (e.g., Park & Shea, 2002; Park, Wilde, & Shea, 2004) sequences that participants would be capable of adapting the movement pattern to unpracticed, but proportional spatial transfer conditions. This type of transfer would be effective because the relative pattern of muscle activation would only have to be rescaled to satisfy the changed spatial requirements. However, it is predicted that transfer would be less effective when the unpracticed spatial conditions required non-proportional changes in the movement pattern. In this situation, the practiced muscle activation pattern could not be simply rescaled but would need to be restructured to optimally meet the demands of the changed spatial requirements.

The data from Experiment 1, which involved 1 day of practice prior to retention and transfer testing, demonstrated participants could successfully transfer to both proportional and non-proportional transfer conditions. Indeed, contrary to initial predictions, performance on the non-proportional transfer test was as effective as the

group that practiced with that spatial configuration on Day 1. This suggests that participants at this stage of practice were relying primarily on sequence order information and had not yet fully structured the sequence and/or optimized the motor commands to the specific movement requirements. This finding is consistent with recent effector transfer findings where effector transfer performance was as effective after 1 day of practice as performance using the effectors used during the practice phase (Whitacre & Shea, 2002; Park & Shea, 2002). However, in Experiment 2, after 4 days of practice, participants were only effective in transferring to the proportional transfer condition. Performance on the non-proportional transfer test after 4 days of practice was no better than transfer after 1 day of practice in Experiment 2. That is, additional practice incremented performance on the proportional transfer tests, but not the non-proportional transfer tests. Consistent with the findings of effector transfer experiments, these results demonstrated that the specificity of the sequence production increases over practice, but that participants remain capable of rescaling the spatial characteristics of the movement sequence even after extended practice.

Experiment 3 observed transfer performance after practicing a “less difficult” dynamic arm movement task. Based on results of effector transfer research with simple (e.g., Lai et al., 2002; Whitacre & Shea, 2002) and more complex (e.g., Park & Shea, 2002; Park, Wilde, & Shea, 2004) sequences, it is predicted that participants will learn the sequence order and begin to structure the sequence early in the practice sessions. Thus, the optimization process can also occur early in practice. The optimization should lead to a connection or linkage between the movement structure and the individual

elements with a greater degree of response specificity. Therefore, it was predicted that the development of response specificity would occur in the “easier” task earlier than in the “more difficult” task. In this regard, Verwey (2001) has proposed that in simpler tasks, relative to a more complex task, the cognitive processor can be allocated to assist with the motor components of execution earlier in practice than in more difficult tasks.

### Sequence Representation and Transfer

Numerous theoretical perspectives have proposed that the structure of a movement sequence is determined independently of the articulatory activities that result in the specific activation of the effectors. These movement dimensions have been variously labeled relative and absolute (e.g., Schmidt, 1975), invariant and variant (Schmidt, 1985, 1988), structural and metrical (Kelso, 1981), higher and lower order (e.g., Fowler & Turvey, 1978), and essential and non-essential (Gelfand & Tsetlin, 1971; Kelso, Putnam, & Goodman, 1983; Langley & Zelaznik, 1984). These distinctions imply that the movement structure dimension, variously labeled the relative, invariant, higher order, or essential depending on the theoretical perspective, is more abstract, involves independent representations/processing and, thus, is potentially scalable in various superficial dimensions (see Schmidt, 1975; for a recent review see Shea & Wulf, 2004). This is in contrast to the other movement dimension, variously labeled the absolute, variant, lower order, or non-essential dimension depending on the theoretical perspective, which is thought to involve more specific processing activities that produce the individual elements of the sequence. More directly, Keele et al. (1995; also see Verwey, 1994) proposed that one processing module is responsible for the organization of

sequential movements (cognitive processor) and another independent module is responsible for generating the specific articulatory commands associated with producing the individual elements in the sequence (motor processor). In support of the notion of an abstract sequence representation, Keele et al. (1995) found SRT tasks involving discrete key pressing to be effector independent. That is, transfer to the contralateral hand/fingers or voice activated responses were produced as effectively as when the participant used the same set of muscles as used in practice. Similarly, Lai et al. (2002) found timing sequences produced by alternately tapping with the left and right hand to be equally well performed when the roles the hands played in the sequence were reversed or a single finger, as opposed to alternating fingers, was used to tap the sequence. These results clearly demonstrate that the movement structure is independent of the specific articulatory activities that generate the specific commands to the effectors.

Recently, Park and Shea (2002), in an attempt to extend the recent effector independence findings to a dynamic movement sequence, allowed participants to practice producing a force-time waveform using one set of effectors and then compared delayed retention performance using the same set of effectors with performance on a transfer test where a different set of effectors was required. In Experiments 1 and 2, contralateral or ipsilateral effector transfer tests were conducted. The contralateral test involved transfer to the opposite limb while the ipsilateral effector transfer test involved transfer where the agonist and antagonist muscle switched roles. In Experiment 3, participants practiced the static, force production task used in Experiments 1. After completing the delayed retention test, participants were asked to produce a dynamic

version of the task. This transfer condition involved considerably different muscle activation patterns, but the relative timing and relative force requirements were the same. The results were remarkably similar across the three experiments regardless of whether transfer was to a new limb (see Figure 5), a different muscle group on the same limb, or whether transfer was from static to dynamic versions of the task. Interestingly, this result has been replicated by Park and Shea (2003) using the long 16-element arm movement sequence used in the present experiments. After one day of practice with the right limb, participants were able to effectively produce the movement pattern with their left limb.

These results provided strong empirical support for the notion of effector independence at least with respect to the movement structure. These findings are also consistent with the proposal that independent computational modules are responsible for sequence and element production (Keele et al., 1995), and the notion of independent cognitive and motor processing mechanisms (Verwey, 1996). Both perspectives argue that the computational module or processing mechanism responsible for organizing the sequence characteristics of the response do so in a more abstract manner than the module or mechanism responsible for formulating the specific motor commands. Similarly, Kelso and Zanone (2002; also see Buchanan, 2004; Criscimagna-Hemminger, Donchin, Gazzaniga, & Shadmehr, 2003) have argued that coordination dynamics and associated changes in task-level attractor states are represented at an abstract, effector independent level of system functioning. Regardless of the theoretical perspective, the bottom line is that at least some characteristics of movements are represented in an abstract, effector independent manner.

While the effector transfer findings are consistent with the notion of an abstract sequence representation that governs the sequential organization of movement, few experiments have systematically determined the extent to which sequential movements can be transferred across other movement dimensions. If the response structure is indeed represented in an abstract manner, as has been proposed, one would predict transferability when circumstances dictate changes in force, timing, and/or spatial requirements. The ability to rescale simple, usually one or two element, movement sequences to changed force (e.g., Whitacre & Shea, 2000, 2002) and/or timing (e.g., Wulf, 1992; Wulf & Lee, 1993; Wulf, Lee, & Schmidt, 1994) requirements have been demonstrated. These experiments were conducted in an attempt to test predictions of motor program theory (e.g., Schmidt, 1975, 1985, 1988). Schema theory, for example, proposed that a generalizable motor program defined a set of invariant features of a motor program (e.g., relative time, relative force, sequence of elements) which could be rescaled in various superficial movement dimensions in response to specific movement demands. In general, this research provided strong support for both the notion that the motor program which specified the sequential features of the movement was represented in an abstract manner and the notion that because of the abstract nature of the sequence representation that the movement structure could be easily rescaled. Importantly, rescaling of the movement sequence resulted in proportional changes in the movement pattern such that relative timing, relative force, and/or relative spatial characteristics of the movement remained intact.

Consistent with the effector transfer experiments, the findings from Experiments 1 and 2 demonstrated that after 1 day of practice the movement structure of complex, dynamic movement sequences could be effectively transferred to unpracticed spatial configurations. This finding, coupled with previous effector transfer findings, provides strong support for the notion that the movement representation is stored in an abstract manner which is independent of the specific muscle activation sequences, at least at this stage of learning. In addition to Experiment 1 and Experiment 2 with a more complex dynamic task, Experiment 3 found evidence of transfer ability of proportional sequences after 1 day of practice in a simple, dynamic arm task. Thus, it appears that the perceptual-motor system is designed to accommodate change. The design feature that permits the fluid transition from one set of conditions to another is the separation (independence) of higher – more general features of the to be learned sequence and lower – more specific features related to the activation of the specific muscles.

#### Practice and Movement Sequence Transfer

While a number of recent studies (e.g., Experiment 1; Park & Shea, 2002, 2003) have demonstrated that movement sequences could be effectively transferred to new muscle groups or to changed spatial configurations, it was not clear whether this transfer ability was a pervasive characteristic of the motor system or was somehow limited to performance relatively early in the practice. Clearly a perceptual motor system which permits a great deal of movement flexibility early in the learning processing, but is capable of optimizing movement specifics with additional practice, has a great deal of intuitive appeal. Park and Shea (2003), for example, conducted an experiment to

determine the effect of practice on the extent to which simple response sequences practiced using one set of effectors could be effectively produced using an unpracticed set of effectors. Given additional practice, it is possible that in an attempt to optimize movement production, effector information becomes more directly linked to the response structure than was observed early in practice (e.g., Park & Shea, 2002). This general phenomenon has been termed coarticulation (Jordan, 1995) and has been shown to influence the production of well-learned movement sequences in speech (e.g., Benguerel & Cowan, 1974; Sternberg, Monsell, Knoll, & Wright, 1978), key pressing (Verwey & Wright, 2004), and in skilled typing (e.g., Gentner, Larochelle, & Grudin, 1988). The effect of additional practice, then, would be a more effective response when the same muscles and activation patterns were required but of little additional benefit when a new set of effectors or activation patterns were required. In the extended practice experiment (Park & Shea, 2002) delayed contralateral and ipsilateral effector transfer tests were compared to a delayed retention test (effector transfer tests counterbalanced). In contrast to transfer after 1 day of practice, after extended practice the movement structure was not effectively transferred to the unpracticed effectors. This suggests that, as the movement sequence was refined during the additional practice, the movement structure became more effector dependent than it was earlier in practice (see Shapiro, 1977 for alternative finding).

Park and Shea (2003), using the long sequence from the present experiment, also provide evidence, that after extended practice, participants structured their response (consolidated or concatenated elements) on an effector transfer test differently than on



the retention test. This was not the case after one practice session. In fact, the sequence organization that was used on the effector transfer test after extended practice was similar to that observed much earlier in practice. Additional practice resulted in a more refined and better scaled movement sequence, which was also less adaptable to effector transfer conditions. When faced with producing the response using a different set of effectors, the additional practice resulted in no additional benefit in terms of the response structure and the specification of force. The Park and Shea (2003) results are remarkably similar to that found in Experiment 2 and 3, in the extended practice groups, where the spatial characteristics of the response sequence were changed, rather than the effectors. In Experiment 2 and 3, additional practice incremented performance on the retention test and the proportional transfer test but not the non-proportional transfer test. Presumably, the movement characteristics that were enhanced through additional practice were such that they could be rescaled to accommodate the changed spatial conditions. However, when the spatial movement requirements were changed in a non-proportional manner the additional practice failed to provide improvement in transfer performance over that observed after only one day of practice. Clearly the additional practice enhanced transfer abilities when the changes in the requirements were proportional because the refined movement structure could be rescaled, but not when they were non-proportional. Indeed, it appeared that participants had to abandon the movement structure developed over the four days of practice when the changes were non-proportional in order to accommodate the subtle change in the position of one of the targets in the sequence. In Experiment 3, participants learned a “less difficult” sequential pattern and demonstrated at even earlier

stages of practice a structural and individual element linkage after just one day of practice that lended toward successful proportional transfer and less ability to transfer to a non-proportional spatial pattern. With extended practice, the non-proportional transfer was unchanged relative to transfer after 1 day of practice. These findings suggest that the principles of transfer early in practice are quite different from those later in practice and vary depending on complexity of the task.

Evidence of the integrity of the movement structure in Experiment 1, 2, and 3 is most clearly observed in the zero crossings in the acceleration traces that demonstrate the controlled rhythmicity of the movement pattern. While after limited practice the movement sequence appeared as discrete steps transitioning from target to target, (resulting in numerous zero crossings) more extended practice allowed the participants to increase the speed of movement by generating a more fluid – rhythmical movement pattern that did not dwell at the various targets/elements, but rather moved continuously between reversal points. This type of transition from discrete to more cyclical movement has also been observed recently in continuous Fitts' type tasks by Buchanan and colleagues (Buchanan, Park, Ryu, & Shea, 2003; Buchanan, Park, & Shea, ; also see Pew, 1974). They argue that this transition from discrete to cyclical over practice indicates the nervous system's propensity for cyclical movement. Indeed, they observed increases in harmonicity over practice even for indexes of difficulty initially requiring relatively discrete movement.

The rhythmical qualities that appeared with extended practice in Experiment 2 were acquired earlier in practice in Experiment 3 with the simpler task. Since participants

seemed to reach the continuous, fluid stage sooner with the simple pattern in Experiment 3, the cognitive, more abstract processor may have been freed up more rapidly to assist with the motor processing duties and to create faster execution time. This is consistent with the notion of dual, parallel processors responsible for the production of sequential motor tasks (Verwey, 2001). Consistent with Verwey's dual, parallel processor model, the simpler sequence in Experiment 3 may have allowed the participants to reallocate the cognitive processor to assist in motor processing demands after less practice in order to create the most efficient movement possible.

One might conclude, then, that in the simple task participants would be able to group a larger number of elements into each subsequence/chunk. The result would be fewer subsequences and faster execution times. However, the data from Experiment 3 demonstrates otherwise. In fact, it appears as though there is a limit to the number of elements that can be grouped into a "chunk" or subsequence. Regardless of sequence difficulty, this is consistent with Verwey's (1996) proposal that the amount of information that can be held in the motor buffer is limited. He proposed that no more than 3-4 elements can be chunked together to form a subsequence. In Experiment 3, even through extended practice, participants tended to only chunk 3-4 items together. It is possible, however, that the simple pattern allowed participants to reach the 3-4 element limit sooner than a more complex task.

The results of these experiments suggest that the independence of the movement structure and movement scaling may be lost over practice with the movement structure and the force characteristics becoming more closely integrated. This can occur at an

even earlier stage in practice with a relatively “simpler” sequence. It seems reasonable that after practice with this type of task that participants attempt to exploit the unique characteristics of the specific effectors. It also seems reasonable that this exploitation benefits response production when the same effectors are used but increasingly limits the extent to which the response sequence is effector independent (also see Proteau, Marteniuk, Girouard, & Dugas, 1987; Proteau, Marteniuk, & Levesque, 1992), but not the ability to rescale the entire sequence.

Although the theoretical proposals of Klapp (1995), Keele et al. (1995), and Verwey (1994) do not make specific predictions about proportional or non-proportional transfer, Schmidt (1975) and Rosenbaum et al. (1984) do make relatively specific predictions about transfer. The general findings of Experiment 2 and 3 are consistent with the predictions of both Schmidt (1975) and Rosenbaum et al. (1984). Schmidt (1975) proposed that a generalizable motor program (GMP) could be rescaled along various parameter dimensions such as amplitude, force, or time. A parameter change in a movement would result in a proportional change across the entire movement sequence while the relative or proportional features of the movement remain intact. The present data is consistent with Schmidt’s proposal and suggest that these tasks could also be scaled effectively in terms of time and force. Schmidt’s (1975) predictions are limited, though, because the tasks Schmidt utilized to reach his conclusions were rapid actions thought to be based upon a single motor program. Shea and Wulf (2004), however, concluded in a re-evaluation of Schmidt’s schema theory that these rules also apply to a broader range of tasks as long as the movement is governed by a stable structure even if

the movement is not controlled by a single motor program. Similarly, Rosenbaum et al. (1984) described an inverted tree branch metaphor to describe the production of movement sequences. He suggested that as long as the learned structure can be used, then effective transfer should occur. This idea supports the proportional transfer success in the current experiments. Thus, the findings from Experiments 1, 2, and 3 provide support for these theoretical perspectives. However, the examination of proportional and non-proportional transfer under various parameter conditions requires further consideration in terms of the generalizability of movement skills as well as the effects of the practice specificity.

## **CHAPTER VI**

### **CONCLUSION AND RECOMMENDATIONS**

In summary, the present findings suggest that the way in which dynamic movement sequences are represented in memory and executed changes across practice and with the degree of complexity. Early in practice the response structure appears to be represented in a highly abstract way resulting in effector and parameter independent performance capabilities. Later in practice, as specific characteristics of the motor system are exploited in an attempt to refine the movement pattern, the movement sequence becomes more precisely represented resulting in enhanced performance when the same effectors and relative movement pattern is required, but less effective when circumstances require the response to be executed using different effectors or different relative movement patterns. Similar practice effects occur when the pattern is simple, but these effects appear at an earlier stage in practice.

The dynamic arm movement task is one method of studying sequence learning. However, my recommendations for future studies include incorporating a multi-joint comparison of transfer. For instance, how does sequential motor learning transfer to and from the wrist and elbow or elbow and shoulder? Are spatial transfer tendencies, proportional and non-proportional, consistent across ipsilateral joints? Experiments 1, 2, and 3 tested normal adults, but future studies could expand into effects on pediatric and geriatric cohorts as well as clinical populations such as Parkinson's Disease or cerebrovascular accidents to further identify how components of sequential learning tasks are affected with injury to specific anatomical locations. In a previous study

including the same dynamic arm movement task, Shea, Park, and Wilde (2004) found that older participants did not necessarily have slower execution rates, as random sequences were performed with no differences between age groups. The older age group was, however, limited by their ability to form and utilize an efficient structure of the repeated sequence that resulted in slower execution times for the repeated sequence trials. Thus, one would predict that an attempt to transfer the relative characteristics of the pattern without maximizing the use of a structure for the sequence that normally occurs with practice would also create limitations in transfer.

The next step along these same lines of research would be to assess other parameters besides the spatial features, moving into timing and force parameter changes both proportionally and non-proportionally. Another follow up study to the current experiments would be to create a more implicit learning task. Participants in my experiments volunteered information and verbalized that a pattern existed and what the pattern was or when it changed to a random sequence. Participants, thus, demonstrated explicit memory ability and relatively soon in practice. Experiment 3 participants verbalizing the pattern sooner than participants in Experiments 1 and 2. With this in mind, future studies could test participants with a more implicit version of the arm movement task. For example, participants could practice the same sequence with random targets between each repeated target. This would likely be a more implicit task in which researchers can observe how spatial transfers are affected by a more implicit level of learning.

Much is yet to be understood about the learning and utilization of sequential motor tasks. The theoretical perspectives regarding spatial transfer of sequences in motor learning will require the development of further empirical support. These experiments have begun such as process as well as identified some novel observations regarding the spatial transfer of movement sequences.



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**APPENDIX A**  
**INSTITUTIONAL REVIEW BOARD APPROVAL**



Office of the Vice President for Research

January 21, 2004

**MEMORANDUM**

**TO:** Ms. Heather Wilde  
Department of Health and Kinesiology  
MS 4243

**FROM:** Dr. Alvin Larke, Jr., Chair  
Institutional Review Board  
MS 1112

**SUBJECT:** IRB Protocol Review

**Title:** "Parameter Change Arm Movement Task"  
**Protocol Number:** 2003-0475  
**Review Category:** Full Review  
**Approval Date:** January 21, 2004 – January 20, 2005

The approval determination was based on the following Code of Federal Regulations: 45 CFR 46 Subpart A. The research involves children and was, therefore, examined against provisions of Subpart D of 45 CFR 46, particularly 46.404 (Research not involving greater than minimal risk) and 46.408 (Requirements for permission by parents or guardians and for assent by children), as well as the current guidelines for inclusion of children in research. The IRB found the research to be of minimal risk to the child, and after considering the age, maturity and psychological state of the children to be enrolled in this study, determined that adequate provisions are made for soliciting the assent of the child and permission of a parent or legally authorized guardian who has been granted authority to consent for medical care including research. The IRB further determined that all children age 7-11 must be asked to verbalize their assent/dissent to participate, and children age 12-18 must indicate their assent in writing.

**Remarks:** None

The Institutional Review Board – Human Subjects in Research, Texas A&M University has reviewed and approved the above referenced protocol. Your study has been approved for one year. As the principal investigator of this study, you assume the following responsibilities:

**Renewal:** Your protocol must be re-approved each year in order to continue the research. You must also complete the proper renewal forms in order to continue the study after the initial approval period.

**Adverse events:** Any adverse events or reactions must be reported to the IRB immediately.

**Amendments:** Any changes to the protocol, such as procedures, consent/assent forms, addition of subjects, or study design must be reported to and approved by the IRB.

**Informed Consent/Assent:** All subjects should be given a copy of the consent document approved by the IRB for use in your study.

**Completion:** When the study is complete, you must notify the IRB office and complete the required forms.

**APPENDIX B**  
**INFORMED CONSENT**



## CONSENT FORM FOR ADULTS

Title: Parameter Change Arm Movement Task

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I have been asked to participate in this study, which determines the time course and the extent to which sequence information is learned and how these sequences are represented in memory. I was selected to be a possible participant because I responded to a posted bulletin. This study will involve 80 individuals who will be tested in the Human Performance Laboratory at Texas A& M University. If I agree to be in this study, I will participate in two to five sessions separated by 24-hour time intervals. The first through fourth sessions will last approximately 40 minutes and the final session will last approximately 30 minutes. In each session, I will sit on a chair and move a lever across a tabletop with the right arm from target to target as quickly and accurately as possible. The arm movement requires minimal force or straining of the arm in normal ranges similar to reaching to touch an object and pulling the arm back toward the body. In the first through fourth practice sessions, I will perform 16 blocks and in the final session 12 blocks each with 160 targets per block. The purpose of this experiment is to determine the extent to which sequence information is learned and is represented in memory.

Participation in this experiment entails low risk for me. In rare cases, I may experience some elbow and/or shoulder fatigue. I understand that participation in this experiment is voluntary. I can withdraw participation at any time without consequence. I understand that I will not be paid for my participation but my parking ticket from the Koldus garage will be validated. There are no personal benefits to the participant. I understand that NO medical treatment will be provided if injury should occur. However, in the unlikely event that I might be injured, the experimenter will call 911.

My results will remain confidential. The researcher has earned a Certificate of Confidentiality. No identifiers linking me to the study will be included in any sort of report that might be published. Research records will be stored securely and only Heather Wilde and Dr. Charles Shea will have access to the records. My decision whether or not to participate will not affect my current or future relations with Texas A&M University. If I decide to participate, I am free to refuse to answer any of the questions that may make me uncomfortable. I can withdraw at any time without my relations to the university, my job, my benefits, etc., being affected. I can contact Dr. Charles Shea and Ms. Heather Wilde with any questions about this study.

I understand that this research study has been reviewed and approved by the Institutional Review Board-Human Subjects in Research, Texas A& M University. For research-related problems or questions regarding subjects' rights, I can contact the Institutional Review Board through Dr. Michael W. Buckley, Director of Research Compliance, Office of Vice President for Research at (979) 845-8585 (mwibuckley@tamu.edu).

I have read and understand the explanation provided to me. I have asked questions and have received answers to my satisfaction. I have been given a copy of this consent form for my records. By signing this document, I consent to participate in the study

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Signature of Participant

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Date

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Signature of Investigator

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Date

If you have any questions regarding the study, please contact Heather Wilde, Texas A&M University, 845-5637, ptwildeone@hlkn.tamu.edu or Dr. Charles Shea, Texas A & M University, 845-4802, cshea@hlkn.tamu.edu.

## VITA

HEATHER JO WILDE

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Department of Physical Therapy  
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### Education

- Ph.D. in kinesiology                      Texas A&M University                      2004  
motor behavior specialty
- M.S. in physical therapy      Texas Tech University Health Science Center      2000  
deans award for excellence
- B.S. in kinesiology                      Angelo State University                      1999  
summa cum laude honors

### Work Experience

- Assistant Professor, University of Texas Health Science Center      2004-present
- Physical Therapist, St. Joseph's Regional Rehabilitation Center      2002-2004
- Kinesiology Instructor and Lecturer, Texas A&M University      2002-2004
- Graduate Research Assistant, Human Performances Laboratory      2002-2004
- Clinical Director and Outpatient Physical Therapist,  
West Texas Rehabilitation Center      2000-2002
- Physical Therapist, San Angelo Community Medical Center      2000

### Professional Associations

- American Alliance for Health, Physical Education, Recreation,  
Dance (AAHPERD), symposium research presentation      2003-present
- Texas Society of Allied Health Professionals, active member      2002-present
- North American Society for Psychology of Sport and Physical  
Activity (NASPSPA), multiple poster presentations      2002-present
- American Physical Therapy Association neurology, orthopedics,  
education, and research section member, research presentation      1997-present
- Texas Physical Therapy Association member      1997-present  
Vice Chair for the Student Special Interests Group      1998-2000